NUCLEAR ENGINEERING VOL. 5 NO. 54 NOVEMBER, 1960

The IAEA in the Balance

ONCE Professor Nadjakov had declared that it was the responsibility of those assembled to discuss the problem of nuclear disarmament, the stage seemed set at the IAEA's Fourth General Conference for the final curtain to be drawn on the effective life of the Agency. The old East-West political battles were resurrected (including the credentials of China), the question of safeguards was coming to a head and it seemed that only nuclear disarmament was required to ensure the complete collapse of this form of international collaboration in the peaceful uses of atomic energy. However, in spite of the harsh words, the generalized accusations, the unconciliatory attitudes, the IAEA continues to operate for at least another year. Perhaps it was saved by the concurrent meeting of the General Assembly of the United Nations which diverted much of the limelight away from the conference, and prevented any of the major points of contention leading to disaster, but this may be a cynical viewpoint and it may be that there is a genuine majority wish for constructive international collaboration in the field.

There would appear to be four separate approaches to the work of the IAEA. The major Western nuclear powers, whilst generous with funds and assistance, seem mostly concerned with foisting responsibility for the implementation of the safeguard clauses, traditionally written into their bilateral agreements, upon the Agency. The underdeveloped countries are members primarily because they hope to obtain something for nothing. There is a group which appears genuinely interested in the Agency's work of establishing standards, working out international rules and regulations, exchanging information and stimulating development without overlapping. Finally the Soviet bloc (perhaps because it did not start it) gives rather the impression that although it is not prepared to completely sabotage the enterprise would prefer the Agency not to exist at all. Yet the Agency is doing good work, and although its record is not particularly remarkable, it is able to point to a year of solid if inconspicuous achievement.

None of this has been completely essential, but all would appear to be eminently worth while; indeed in the absence of an international organization such as the Agency, the establishment of internationally consistent legislation on such matters as waste disposal, insurance and liability, would be almost impossible. The cost of the Agency, too, is negligible in comparison with the benefits that can accrue, and it seems parsimonious in the extreme the way the budget of the IAEA is held to the minimum, not on the basis that this keeps the Agency's personnel on their toes and aids efficiency, but from purely niggardly motives. The Agency itself is partly to blame for this, in both its organization and administration. The existence of a voluntary fund quite separate from the regular fund seems most unnecessary, and leads to discussions on finance on a remarkably petty scale. If the Agency, however, had used the whole of last year's fund perhaps a more generous response would have been forthcoming this year; but for the United States' contribution, the total sum contributed would be pitifully small. Accounts of the financial discussions in fact, read much more like the proceedings of a local fête committee than of an international body.

Once the necessity for safeguards was written into the original constitution some controversy was inevitable. If, in the past four years, the Western powers had got over their obsession that the secret desire of all nations was to create a stock of pure fissile material, or if, alternatively, the disarmament talks had been completely successful, the problem would have been much easier. But the West was emphatic that safeguards must be retained, the group of Eastern countries, headed by India, was passionately of the opinion that this entailed a violation of sovereign rights (although one would have thought that seeking assistance from the Agency was itself an acknowledgment of national insufficiency) whilst the Eastern bloc was careful to stir the pot of contention as often as possible, and used every opportunity for sneering at the American attitude, including (with some justification) the offer for four reactors to be placed under international inspection. It is fortunate that there was a sufficient number of countries who felt either that the recommendations of the board of Governors were sufficiently close to the optimum compromise for further argument to be useless, or, alternatively, that the safeguards subject was so academic as to be lacking in serious import. As a result, the fifteen power motion, in effect accepting the board's recommendations, but requesting flexibility in the board's negotiations with any country, was finally accepted. It still remains to be seen whether such an arrangement is workable, and India in particular expressed the strongest opposition to it, and implied that she would not necessarily accept any safeguards relating to materials other than of weapons grade. It is to be hoped, however, that this was merely a final fling in the debate, rather than a considered policy. The pink (if not actually red) herring of centrifuging was also, of course, dragged across the scene, but created less of a stir than newspaper reports might have indicated (centrifuging was, after all, first examined in the early 1940's). It is to be hoped that this technique of separating isotopes will not figure more prominently in subsequent meetings, and be used as a further means of prolonging controversy on the safeguards question. None the less the Agency has, at least on paper, successfully surmounted its worst hurdle to date but unless it can give more point to its solid successes, gain a more international appreciation of the work it is doing, and concentrate its efforts on those items of assistance and co-ordination where it can do most good, its chances of continued survival will still remain in the balance.

Merging the Groups

ALTHOUGH no announcement has been made, G.E.C. (the only competitor at the end) have acknowledged that they will not be awarded the contract for the Sizewell station, and this must mean that the award will be to the English Electric—Babcock and Wilcox—Taylor Woodrow group. If G.E.C. is considered as a single concern, this means that the Generating Board has once again by-passed the company. If on the other hand it is thought of as a partner in the United Power Company, the Generating Board has again placed its contract in strict rotation. The significance, therefore, of this competitive tendering must once again be raised, and doubts expressed either on the validity of the awards or the necessity for competition and the expense of producing abortive tenders. It is of course true that the company most concerned in receiving a contract has the greatest incentive to cut the price, and this has a tendency to result in the lowest price being submitted by the company next in sequence. Must there be competition, however, for this incentive to be present, and would it not be reasonable, until the rate of construction exceeds the average of one a year, for a period of negotiated tenders to be tried? Alternatively could not all future Magnox stations be negotiated, starting off with Oldbury? This would in any case effectively happen if there were a further contraction of the groups, resulting from the proposed G.E.C.-English Electric merger.

Although nuclear energy tends to figure somewhat largely in company chairmen's annual reports, the merger arises from problems met in the highly competitive worlds of generating and switchgear equipment, and the domestic appliance market. It is difficult to believe that when this merger has been completed the result will be a merger also between the United Power Company and English Electric; certainly this is a situation that the Generating Board would not welcome. So far no satisfactory compromise has been devised, the companies concerned being preoccupied with weightier matters.

Should, however, it be decided that there should at first be only two groups, we cannot believe that this is a state of affairs that would last for long. Either one of the units (such as APC) or alternatively one of the companies (such as Babcock and Wilcox) would be strongly tempted to break away. There is, after all, no *a priori* reason why the prime contractor should be an electrical company, and indeed there are strong arguments for suggesting that the prime contractor should be either a civil engineering organization or a boiler organization, particularly if, at some future date, the CEGB moves away from the turnkey contract to a contract system more closely analogous to the one adopted for conventional stations. Integral design is, of course, a problem in this case, but starting with the AGR, the Generating Board's own strength will be something to be reckoned with, and it may well feel capable of undertaking the broad plant optimization itself, and succeed in breaking the total design up into specific sections which can then go out to tender as separate entities. Whatever the final outcome, and whatever the economies achievable by negotiated tenders, from the consumer's point of view there is no danger of there being an entrenched monopoly, more interested in routine than in progress.

The Dangers of Coal

IT is now nearly four years since we published the satire by Professor Frisch " On the Feasibility of a Coal-fired Power Station " (*Nuclear Engineering*, December, 1956, p. 368) which pointed the dangers associated with the oxidation of carbon in the presence of nitrogen, and the formation of carcinogenic compounds. The Report of the Committee on Air Pollution (Cmnd., 9322) is, however, a serious document, and makes frightening reading. It quotes, for example, that the railways used 13.8 million tons of solid fuel in 1953, and from it produced 0.3 million tons of smoke, 0.1 million tons of grit and dust, and 0.4 million tons of sulphur dioxide. Whereas a great deal can be done about smoke, grit, and dust removal, very little can be achieved with simple plant, in scrubbing out the SO_2, and whilst the establishment of smokeless zones has done a great deal to clean the local areas of grime and dirt, the smokeless fuels (and this applies also to oil) are emitting the same amount of sulphur oxides as the smoky fuels.

Against such a background, the potential health hazards of an atomic energy programme seem somewhat minor. One of the dangers of radiation is its insidious nature, and the fact that special instruments are required to detect it, but this is even more true of sulphur dioxide, and D.S.I.R.'s latest report into the Investigation of Atmospheric Pollution would indicate that even the measurement of SO_2 concentration in the atmosphere by special instruments is far from satisfactory.

It is small wonder, therefore, that the Atomic Energy Authority and the CEGB should now be preparing the ground for the eventual installation of nuclear power stations near populated areas, by making odd references to the possibility at regular intervals (the latest was in Vienna). A small amount of argon-41, (an inert gas!) seems a small price to pay for the elimination of tons of sulphurous fumes. We are relieved to see that in the latest colliery accident, the seven trapped miners were finally brought to the surface unscathed, but how long are we to continue indulging in this highly dangerous practice of coal mining, followed by this insidious practice of coal oxidation? We congratulate the EDA on its timely pamphlet " Nuclear Power to Clear the Air."

It is not even as if coal were cheap. The increase in the price of coal to the Generating Board, 5s. per ton (so much less than to the domestic consumer), will make an average difference in the cost per kilowatt hour in the U.K. of 0.038d. This includes a number of power stations working at relatively low efficiencies, and for a modern coal-fired station, one would expect the increase to be of the order of 0.028 to 0.03d. If one now refers to the curves used by Sir Christopher Hinton in his lecture to the Royal Society one sees that the margin between the anticipated cost of power from Trawsfynydd and that from a conventional station is very small indeed, and the anticipated generating costs of Dungeness and Sizewell are definitely below. Admittedly there is many a slip, etc., but it now appears that the Stockholm lecture might not have been so far out after all, and that the Coal Board, by this simple act, has redressed the economic balance back in favour of nuclear generation.

The world's largest ship, *U.S.S. Enterprise*, is moved to an outfitting dock after launching at Newport News, Virginia, on September 24. Powered by eight PWRs supplied by Westinghouse, *Enterprise* is 1,100 ft long and 250 ft wide across the flight deck. Estimated speed is 25 knots.

World News

International

THE FOURTH GENERAL ASSEMBLY of the International Atomic Energy Agency was held in Vienna from Sept. 20-Oct. 1.

On the thorny problem of safeguards (that material and equipment should not be diverted to military uses) a fifteen power resolution has been approved by the IAEA General Assembly. This takes note of the principles of procedures provisionally approved by the Board but invites the Board before giving effect to them, to take into account the views expressed in the General Conference. An amendment to include the stipulation that agreements should be drawn up with regard to the principle of non-discrimination was also adopted. The chief opposition came from the Soviet bloc and from five Eastern nations headed by India.

Additional approval was given to proposals: that the Director General should study the possibility of selling IAEA publications in the local currency of member states; that the Board of Governors should liaise more closely with its Scientific Advisory Committee; that an international exchange of abstracts should be arranged; that co-operation in the field of radiation and neutron standards with the International Bureau of Weights and Measures and other international organizations should be explored; and finally that the fifth General Conference should convene in Vienna on September 26, 1961.

CONSIDERATION is to be given to the establishment of a theoretical physics centre under the auspices of the IAEA. The Director General is required to study and make a report on this question at a later date.

AGREEMENTS for co-operation have been severally reached between the IAEA and the Inter-American Nuclear Energy Commission, the Organization of American States and the European Nuclear Energy Agency—although this last is in reality a formalization of a state already existing. A proposal that consultative status should be granted to the World Federation of Trade Unions was rejected.

FIVE NEW NAMES are added to the membership of the IAEA—Ghana, Chile, Colombia, Mali and Senegal—bringing the total membership to 75. The General Assembly agreed that increased representation for African States was now necessary on the Board of Governors. Succeeding Indonesia, Netherlands, Peru, the United Arab Republic and Venezuela on the Board of Governors for the next two years will be Argentina, El Salvador, West Germany, Iraq and Thailand. The new membership for 1960-61 in addition to the above thus includes Australia, Belgium, Brazil, Bulgaria, Canada, Ceylon, Finland, France, India, Japan, Mexico, Poland, The Philippines, Spain, Union of South Africa, United Kingdom, U.S.A. and the U.S.S.R.

MR. A. D. McKNIGHT of Australia was unanimously elected chairman of the new board with the two vice-chairmen, Professor Nadjakov of Bulgaria and Dr. Fernandez of Mexico.

AGREEMENT was given for the 1961 regular budget of IAEA to total $6,186,000 of which the U.S.A. would contribute 32.43%, the U.S.S.R. 12.6% and the United Kingdom 7.2%. The working capital for 1961 remains $2 million and the operational programme financed by voluntary contributions was set at $1,800,000. To date approximately $1 million to this last fund has been promised, three-quarters of this coming from the United States, of which half a million dollars is unconditional. Furthermore the U.S. has agreed to match contributions in excess of the $1 million mark until a sum of $1¼ million is reached. The U.S.S.R. was not prepared to make further contributions until the $125,000 made available last year had been used.

GAS CENTRIFUGING was in the headlines recently. The development work done by Degussa and other W. German companies attracted the attention of newspapermen who suggested that if the process were successful, nuclear weapon material could be produced in secret at a lower cost. This, they argued, would inevitably mean an increase in the membership of the four-member nuclear "club." More knowledgeable observers have pointed out that the process is not fully developed and that therefore capital cost and running cost of centrifuging uranium hexafluoride can only be estimated. There is, as yet, no evidence to indicate that centrifuging can be cheaper than the diffusion process.

Senor Don Alfonso Rizo Patron, Peruvian Minister without Portfolio visited Hinkley Point on October 8. The photograph shows (left to right) Mr. V. H. Blondell, Taylor Woodrow, site agent, Mr. R. Wall, resident site superintendent, Mr. T. Latimer, Board of Trade, and Senor Patron.

DRAFT REGULATIONS governing the transport of radioactive materials were approved by the General Assembly and strong recommendations made that these should form the basis for national legislations. The Central Office for International Railway Transport is prepared to adopt the major part of the recommendations at its meeting in December and the International Civil Aviation Organization has stated that they could be incorporated within the framework of IOAO's conventions.

AN IAEA MISSION to Latin America left Vienna on October 16. This, the sixth mission sent out by the Agency, will visit Mexico, El Salvador, Guatemala, Peru and Paraguay to advise ways and means of obtaining IAEA assistance.

INFORMATION CENTRE for radioisotopes is to be established by Euratom in collaboration with isotope producers.

U.K.

THE U.K. AEA has decided not to go ahead with the construction of ICSE, the Intermediate Current Stability Experiment, in view of the total design and development effort necessary to bring the project to a successful conclusion. It has recently become clear that the initial estimate of cost (£1½ million) would have to be at least doubled and the AEA has concluded that it would be more economic both in money and manpower to pursue research with smaller machines.

ICSE was to be a torroidal machine with hard core geometry (i.e., an internal conductor) and was designed to give a stable discharge according to present theory. Although the main Authority effort will be related to the pinch effect alternative geometries will be examined and the hard core geometry will be included in the programme but as a smaller machine. This change in emphasis does not affect the Culham site which will still be built up as the centre for thermonuclear research and will progressively take in those experiments at present being conducted at Harwell and Aldermaston.

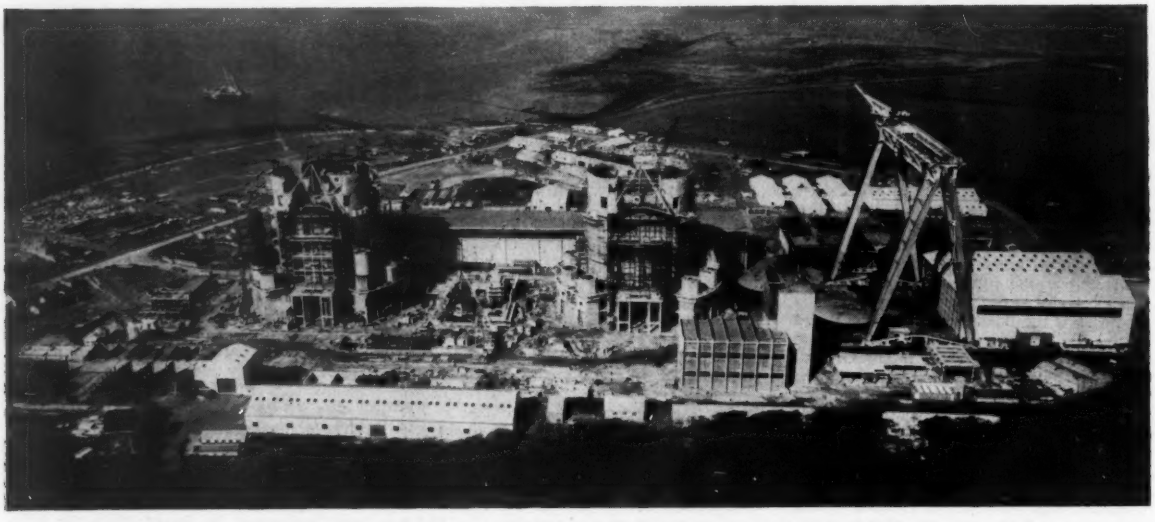
CIVIL ENGINEERING WORK at Hunterston is substantially complete and the pressure vessel for reactor No. 1 is now being prepared for stress relieving. Labour troubles in the fabrication shop have led to a rephasing of the mechanical construction and only one boiler has yet been erected. The programme now calls for the first reactor to go on load at the beginning of 1963, the second following in the autumn. The delay has allowed a complete redesign of the core away from the Calder style to an octagonal block structure with keys and keyways on the vertical faces similar to the design adopted by TNPG for Dungeness. It is likely that the final figure for construction costs will have risen to £50 million by the time the station is complete.

SOLID STATE PHYSICS DIVISION has been formed at AERE, Harwell. Dr. W. M. Lomer, at present head of the Theoretical Physics, will take over the new division.

AN EXHIBITION on atomic energy opened in Edinburgh (at the Royal Scottish Museum) on October 15 and will continue until October 29.

U.S.S. SCORPION—America's twelfth nuclear submarine—visited Portsmouth on October 4.

ANNUAL REPORT of the Advisory Council on Scientific Policy has this year been published as a White Paper (Cmnd. 1167). This independent assessment of the U.K.s scientific effort whilst pointing out a number of deficiencies, particularly in engineering, is on the whole encouraging, more especially the increased level of industrial research. In the sections dealing with the distribution of effort no suggestion was made that atomic energy attracted an unfair or undesirably large fraction—a matter for disappointment for those who enjoy decrying the national programme.



An aerial view of the Hunterston station which G.E.C. and Simon-Carves are building for South of Scotland Electricity Board. The first steam raising unit of reactor A can be seen on its plinth.

Austria

FIRST AUSTRIAN REACTOR — a water moderated tank-type supplied by AMF—is now in operation at Seibersdorf, near Vienna. Dr. Adolf Schaerf, President of Austria, Chancellor Julius Raab and Mr. John C. McCone, chairman, U.S. AEC were amongst those present at the dedication ceremony on September 29. The reactor—AMF's 10th research unit to go critical—will operate in the power range of 5 to 12 MW. A remotely operated device can be driven through the shielding to give direct access to the core for large experiments. Fuel for the reactor was supplied by M and C Nuclear.

Australia

REWARDS for discovering uranium sources will continue to be paid to prospectors, Senator Spooner said recently. In spite of the present cut-back in uranium demand the Government believes that in the years to come there will be an increasing demand for the metal.

Brazil

DECEMBER 1 is still the deadline set for the completion of the specifications for Brazil's first nuclear power station. International tendering will be sought, probably in January, next year.

Canada

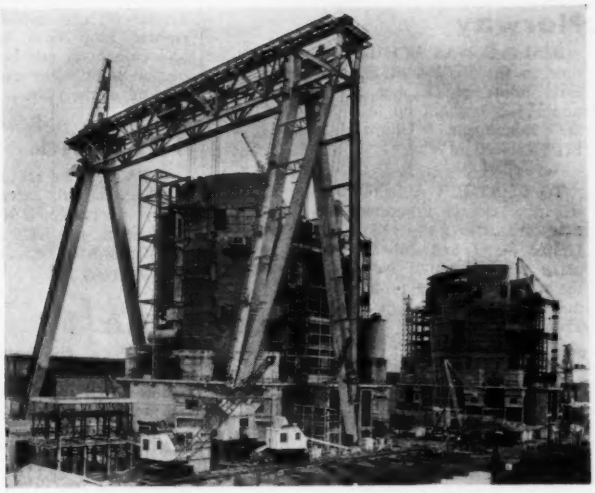
ZED-2 went into operation at Chalk River on September 7. The assembly is now being used for a series of experiments.

France

DELIVERY of 3,000 t of nuclear graphite for EDF 2 at Chinon is now complete. The graphite was produced by Pechiney at its Chedde works (Haute-Savoie) following a process jointly developed by Pechiney and CEA. Designed for a hexagonal pile patented by CEA, the graphite was supplied in bar form, in circular sections. The effective cross section is 3.75 mb.

DUMPING OF RADIOACTIVE WASTE into the Mediterranean by the French CEA has been postponed because of the objections voiced by local authorities in the area. Originally it was planned to dump 6,500 containers in a 7,000-ft. deep halfway between the mainland and Corsica. Euratom's scientific and technical committee had previously given a favourable opinion on the proposal. M. Francis Perrin, High Commissioner for Atomic Energy, has now set himself the task of convincing various coastal authorities that there is no danger in the dumping.

To Hawker Siddeley Nuclear Power goes the honour of supplying the first British export reactor to go critical in a European Common Market country. The LFR—Low Flux Reactor—is installed at RCN's Petten establishment in the Netherlands.



Hunterston's first boiler for reactor A being lifted into position.

Finland

FUEL for the 100 KW Triga Mark II training and research reactor supplied to Finland by the U.S.A. through the IAEA would be charged at $42,000. The U.S. has decided, however, that the material comes within the grant of $50,000 of enriched uranium donated to the Agency at the Third General Conference, so unless a further immediate requirement is forthcoming Finland should receive the fuel free of charge.

West Germany

NUCLEAR SHIP PROGRAMME costing £5 to £6 million is to be initiated in West Germany according to a report attributed to the Hamburg City Government. Financial support is expected from Euratom; the West German Atomics Ministry and W. Germany's four coastal provinces will share the remainder of the cost.

SITE WORK for the Schulten high-temperature reactor has begun in the Stetternich forest near Jülich. The cost—about 40m. DM—will be shared by the German Bund and AVR.

NEXT ACHEMA (chemical engineering exhibition) takes place from June 9 to 17, 1961, at Frankfurt/Main.

Hungary

SIR JOHN COCKCROFT, member U.K. AEA, visited Budapest as guest of the Hungarian Academy of Science during September. According to the Hungarian news agency the possibilities of co-operation were discussed.

Japan

LONG-TERM AGREEMENT for the manufacture in Japan of special types of nuclear-grade graphite has been concluded between General Electric Company and Nippon Denkyoku Kabushiki Kaisha. The Japanese company is a graphite producer.

India

REQUESTS TO TENDER for the first Indian nuclear power station are scheduled to be sent (on an international basis) to manufacturers this week. The proposed site is near Tarapur, about 62 miles north of Bombay, and the specification calls for a 300 MW station.

Italy

AN OFFER of $30,000 has been made by Italy to be used for the extension of the activities of the IAEA's laboratory or for the purchase of additional equipment.

Monaco

FOLLOWING DISCUSSIONS on marine disposal of active wastes Monaco has offered to put at the disposal of the IAEA for three years the facilities of the Oceanographic Institute plus a yearly contribution of $40,000 for research in this field. The details of the arrangement should be settled by the end of the year. Sea dumping is still clearly a subject which causes wide concern and the IAEA was urged to establish a register to take account of what was being done. The major problem continues to be the establishment of concentrations of activity which can reasonably be discharged direct into the sea but even contained dumping is strongly opposed in some quarters.

Netherlands

LOW FLUX REACTOR—a JASON supplied by Hawker Siddeley Nuclear Power—went critical on September 28 at the research centre at Petten. LFR has a capacity of 10 kW with a neutron flux of 1.5×10^{11} n/cm² sec.. Fuel is 4.3 kg of 90% enriched uranium.

Norway

BOILING WAS ACHIEVED for the first time in the BHWR at Halden during the early hours of October 5. The reactor power was brought up to 2 MW(e) during the experiment. Ultimate capacity of BHWR is 20 MW(e).

TO FURTHER A SCHEME for a joint scientific research programme on the evalution of reactor physics data (to which the United States had indicated that it would make contributions), Norway has offered the use of the zero power reactor NORA due to become critical in January next year. The moderator can be light or heavy water and one natural and one enriched core is already available. For the joint project the U.S. would make available a 3% enriched core which has been used for development work on the *Savannah*. The proposal is still under discussion.

South Africa

A NUCLEAR RESEARCH CENTRE for the Universities of Cape Town and Stellenbosch is to be built at a cost of £500,000. A 300-acre site is being surveyed at Faure, near Cape Town. Already £135,000 has been donated towards the capital cost.

Spain

DESIGN STUDY for a multi-purpose nuclear power plant has been completed by Atomics International. The study was made at the request of Junta de Energia Nuclear and the plant would have facilities for training as well as a 30 MW(e) generator. Coolant would be organic with a heavy water moderator.

Sweden

AKK—a combine of Swedish private and municipal power producers—have been granted a permit to build a nuclear power station at Simpvarp on the Baltic coast. Tenders for a 50- to 60-MW enriched uranium reactor have been submitted by ASEA and Nohab on one hand and by Kockums on the other. The order will be placed by the end of the year.

Thailand

IAEA is to be asked for nuclear material and to administer safeguards against misuse. A research reactor is at present being erected in Bangkok with United States assistance and is scheduled for completion towards the end of next year.

U.S.A.

LICENCE for operation of a 10 kW pool-type training reactor has been issued to the University of Maryland. The reactor has been supplied by Allis Chalmers.

A PUBLIC HEARING was convened by the AEC on October 18 to consider the issuance of an operating licence for the 60 MW(t) heterogeneous, water cooled and moderated Plum Brook reactor at Sandusky, Ohio. The National Aeronautics and Space Administration will use the reactor for nuclear systems research.

GRANTS FUND of $10,000 for university graduate students and junior professors has been established by AMF's research and development division.

ORNL is now producing the short-lived radioisotope calcium-47.

BSD EQUIPMENT, supplied by Plessey Nucleonics to Canadian Westinghouse, will be installed in the Westinghouse Test Reactor at Waltz Mill, Pennsylvania.

DRESDEN was dedicated on October 12. The 180 MW reactor built by General Electric was extensively featured in the October issue of *Nuclear Engineering*.

OPERATING LICENCE for a liquid fluidized bed reactor which has been in course of development for five years has been issued to the Martin Company of Baltimore by the AEC. This reactor has a suspended bed of pelletized fuel in an upward moving current of water. This acts both as coolant and moderator and eliminates the need for conventional control rods.

JOINT AEC-NASA nuclear propulsion office to consolidate the development of nuclear energy for space propulsion has been announced by the AEC. Harold B. Finger, chief of nuclear propulsion for NASA, will be manager of the joint office. The deputy manager will be Milton Klein who has been assistant manager for technical operations of the AEC's Chicago operations office.

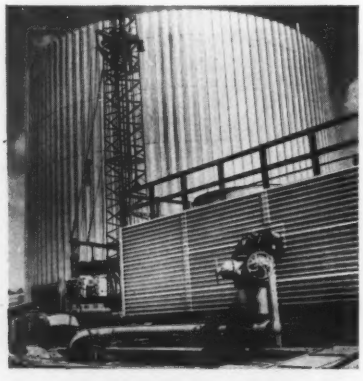
WESTINGHOUSE TEST REACTOR will provide test irradiation and related services for the AEC under a contract signed between the commission and Westinghouse.

INVITATION to submit proposals for design fabrication and manufacture of a reactor pump seal have been invited by the AEC's New York office. The seal is intended for pumps with a capacity of 40,000 g/m; it must operate satisfactorily at temperatures of 600° F and pressures of 2,500 p.s.i. Conditions call for a dynamic head of 150 ft and pump speed of 1,800 rpm. Leakage must be less than 1 g/h.

PRDC, sponsor of the 100 MW (e) Enrico Fermi fast breeder has reported to the AEC that "all significant construction work" would be completed by October 15. The U.S. Supreme Court review of the Court of Appeals decision on the reactor construction licence will not take place before next February.

Yugoslavia

GRANTS totalling $350,000 are to be made by the U.S. in support of Yugoslavia's nuclear programme. Over half this sum will go towards the purchase of a TRIGA Mk. 2 from General Atomics. The remainder will enable the Boris Kidric Institute to build a hot laboratory.



Part of a new $6m nuclear research centre for the Austrian Study Group for Atomic Energy was dedicated on September 29. (Above) AMF have supplied a 5 to 12MW water moderated tank-type research and training reactor. (Right) The visitors to the centre, which is located at Seibersdorf near Vienna, included Mr. Freeman Matthew, U.S. ambassador to Austria, accompanied by (left) Mr. Lacy L. Herrman, director general of AMF's new Austrian subsidiary, and Dr. Michael J. Higatsberger, general manager of the Austrian group.

Heat Transmission with Boiling

by G. S. EMMERSON, M.Sc., A.R.C.S.T., A.M.I.Mech.E., P.Eng.(Ont.)

(*University of Western Ontario, Canada*)

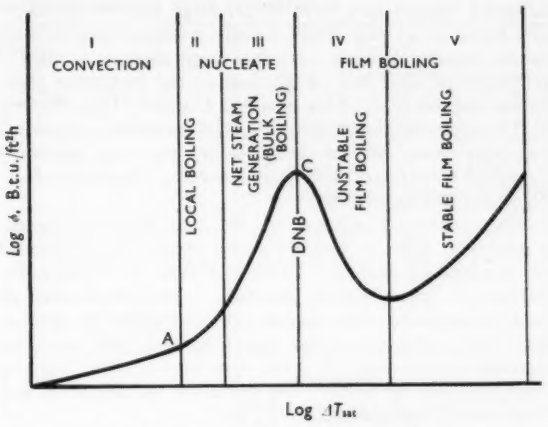


Fig. 1.—Regimes of boiling heat transfer.

IN the early days of power reactor development, boiling in a liquid-cooled and moderated reactor was regarded with apprehension, mainly but not solely on grounds of nuclear stability. The direct generation of steam in the reactor core appeared to offer little prospect of proving feasible. As the result of extensive testing and development, mainly in the United States, this picture has changed. The boiling water reactor is established, and some measure of local boiling is now regarded as acceptable in the normal operation of the so-called pressurized water reactor, originally designed to avoid any boiling of the coolant. Indeed, some thought is now being given to the possibility of permitting net steam generation in the hottest channels of the PWR. The advantage of some boiling in a convection cooled reactor essentially lies in the higher temperature of coolant attainable for the same fuel element temperature and heat transmission rate. It can now be said that water-cooled reactors differ in principle only in the amount or stage of nucleate boiling tolerated in the core. There is too, an economic optimization involved in the final choice of permissible boiling for a given power.

The subject of boiling heat transfer is now receiving widespread attention and it is the purpose of this contribution to review and discuss the rapidly growing store of existing knowledge of this subject and its background, with special reference to nuclear reactor applications.

Regimes of Boiling

The regimes of boiling heat transfer are most conveniently illustrated by the "Boiling Curve." This curve, Fig. 1, is obtained from experiments carried out on an electrically heated wire immersed horizontally in a bath of water. Different conditions prevail in a heated channel, but the characteristics of the boiling regimes remain the same.

As the temperature of the heating element (T_w) rises above that of the liquid, the liquid in contact with the heating element rises in temperature and moves by convection into the body of the liquid. At some stage the liquid in contact with the heater is superheated, and if there is a free surface, as in pool boiling, the superheated liquid rises to this surface, and evaporates. The prevailing heat transfer mechanism here is convection, and this is regime I.

When the temperature of the surface exceeds the local saturation temperature by a few degrees, a stage is reached (point A) at which bubbles begin to form within the boundary layer of superheated liquid, at preferred locations on the heater surface, then collapse on the surface or in the adjacent layers of liquid. This stage is given the name of Local Boiling, regime II. When the bulk temperature is below saturation, local boiling is also called Subcooled Boiling. As ΔT_{ws} continues to increase, the rate of bubble formation increases rapidly and the heat flux rises very markedly until large bubbles form and transport the vapour into the body of the liquid and thence to the free surface or steam space ("Bulk boiling" or "Net Steam generation"), regime III. Regimes II and III fall under the general designation of Nucleate Boiling.

At some particular value of ΔT_{ws}, depending on various factors such as the nature of the liquid, pressure, etc., the bubbles are so numerous that they begin to coalesce and with an increase in ΔT_{ws} of a few degrees form an

NOMENCLATURE

c	Constant pressure heat capacity, B.t.u./lb °F
D	Hydraulic equivalent diameter, ft
D_i	Heated perimeter, ft
G	Mass velocity, lb/ft²h
g	Acceleration due gravity, ft/h²
g_o	Conversion factor 4.17×10^8 (lb_m) ft/h² lb_f
h	Heat transfer coefficient, B.t.u./ft²h °F
H	Enthalpy, B.t.u./lb
H_{BO}	Enthalpy at burn-out location=Hin.+Q/W
J	Joule's Equivalent, 778 ft lb/B.t.u.
K	Thermal conductivity, B.t.u./ft²h °F
L	Length of heated channel, ft
N_{pr}	Prandtl number—dimensionless
P	Pressure, lb/ft²
Q	Heat Supplied, B.t.u./h
S	Distance between parallel heat transfer surfaces
T	Temperature, °F abs.
ΔT_{sat}	Superheat, $\Delta T_{ws}=(T_w-T_s)$, °F
ΔT_{sub}	Subcooling, (T_s-T_L) F°
U_b	Velocity of liquid bulk, ft/sec
W	Mass flowrate, lb/h
α	Thermal diffusivity, ft²/h
ϕ	Heat flux, B.t.u./ft²h
$\lambda=h_{fg}$	Latent heat of vaporization, B.t.u./lb
ϱ	Density, lb/ft³
σ	Surface tension, lb/ft
μ	Viscosity, lb/ft h

Subscripts

BO	Burn-out
$b=L$	Liquid (bulk)
c	Critical
f	Saturated liquid
g	Saturated vapour
s	Saturation
v	Vapour
w	Wall (heating surface)

adhering vapour film from which large bubbles occasionally break away and which rapidly collapses and reforms in an unstable fashion. At this stage there is a marked reduction of heat flux on account of the insulating effect of the vapour film. This is called Unstable Film Boiling, or Transition Boiling, regime IV. The maximum at point C has been given several designations, but most generally "Critical Heat Flux" and more recently, "Departure from Nucleate Boiling (DNB)."

With continued increase of ΔT_{ws}, the heat flux reaches a minimum value at which a stable vapour film is formed on the heating surface. From this film, an orderly discharge of large bubbles proceeds. The mechanism of heat transmission then becomes primarily one of conduction and radiation across the film and the heat flux increases again with ΔT_{ws}, but now very slowly. At this stage, the heating element will reach the melting point and "burn-out" will occur.

With a self-heating element, such as an electrical resistance element or nuclear fuel element, the transition from nucleate to film boiling can occur very rapidly, as after the DNB point, the decreasing heat transmission rate and the rapid increase in ΔT_{ws} have a cumulative effect, one upon the other, until stable film boiling is established. Because of this the heat flux at DNB is regarded as the burn-out heat flux for reactor design purposes. In experimental investigations of the unstable regime (IV) it is necessary to resort to non self-heating elements, such as a tube heated by condensing steam.

Mechanism and Correlations

No correlation has yet been established to govern the boiling curve over all regimes, although separate correlations have been developed, theoretically and empirically for the convection, nucleate boiling and film boiling regimes with varying limitations. Attempts, too, have been made to establish equations for the transition regions; i.e., between regimes I and II, at DNB, and between IV and V. Of these, DNB, or the critical flux region has been of the greatest importance and consequently the most widely studied. The study of DNB is closely associated with that of the unstable film boiling regime (IV) and the transition to film boiling. The criteria for the prediction of the ΔT_{ws} at which film boiling begins can be expected to come with a knowledge of the unstable film boiling mechanism. This subject is discussed later. The I-II transition is much less important and has been comparatively neglected although some attempts have been made to establish equations for this region, both in the U.S.A.[28] and U.S.S.R.

Heat transmission in the convection regime has, of course, been well documented; the Dittus-Boelter, Colborne and Sieder-Tate correlations having gained general if not unqualified acceptance. The film boiling regime, too, is satisfied within limits by the Bromley [43,47] equation and modifications thereof although considerable gaps exist. Much greater difficulties arise, however, in the remaining regimes.

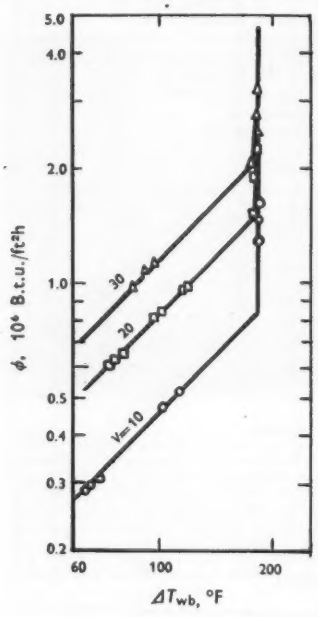


Fig. 2.—Effect of fluid velocity (expressed in ft/sec) as the regime changes from convection to nucleate boiling[47]. System pressure is 2,000 p.s.i.a. and bulk temperature 460°F.

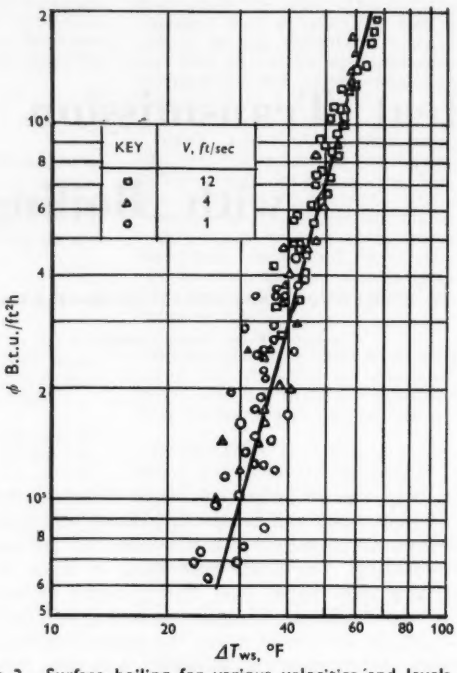


Fig. 3.—Surface boiling for various velocities and levels of subcooling[43].

Nucleate Boiling

Although by high-speed cine photography the activity under the various regimes has been observed, the mechanisms of nucleate boiling and transition to film boiling have not yet been established beyond dispute. In the case of nucleate boiling, it seems simple enough to state that the remarkable increase in heat flux is due to the observed agitation of the vapour bubbles, and while this is a satisfactory explanation, it has not proved sufficient in itself for the development of a theory.

Several hypotheses have been presented and for a detailed description of these see references 1 and 2. These hypotheses more or less reduce to four:

(1) Random micro-convection excited by bubble activity in the normally laminar sublayer.[3]

(2) The bubbles act as surface roughness.

(3) When a bubble grows it absorbs latent heat of vaporization which it returns to the liquid when the bubble collapses, and during bubble growth, liquid at the hot side of the bubble is vaporized and moves as vapour to the cold side of the bubble where it surrenders its latent heat to the liquid bulk.

(4) In addition to (3), the bubbles also transfer heat during their growth by pushing a quantity of hot liquid from the heating surface into the main stream in a kind of pumping action.[2]

The greatest difficulty in the way of developing a relationship to govern the boiling process is the large number of variables which influence the rate of formation and of subsequent growth of the bubbles. The nature of the

heating surface, the presence of impurities (solid or gaseous), the nature of the liquid (including surface tension), and above all the pressure, all for some time have been known to have an influence[43]. A recent refinement[59] is that nucleation occurs from pre-existing gas-filled cavities on the heating surface and that the wall superheat at which such a cavity becomes active is determined by the fluid properties, notably surface tension. It is interesting to note, however, certain unexpected exceptions from the criteria governing convective heat transfer: The heat flux in nucleate boiling in a given circumstance is independent of the velocity of the liquid stream (Fig. 2), and of the geometry of the heating surface. Evidently the process occurs within the boundary layer. It is also independent of the liquid bulk temperature; the driving potential is ΔT_{we}, regardless of the degree of subcooling of the liquid bulk (Fig. 3).

TABLE I. NUCLEATE BOILING HEAT TRANSFER

EQUn.	Ref.	Pool Boiling	Notes
1	4	$\frac{C_L \Delta T_{sub}}{\lambda} = a\left(\frac{\phi}{\mu L \lambda}\sqrt{\frac{g\sigma}{g(\varrho_L - \varrho_V)}}\right)^{0.33}\left(\frac{C_L \mu_L}{k_L}\right)^{1.7}$	Coefficient 'a' is determined experimentally for a given combination of liquid and surface and is independent of pressure. Combination / a: Water on Platinum .. .. 0.013; Water on Brass .. .. .. 0.0060 (4); Diphenyl on Stainless Steel .. 0.0086; Meta-terphenyl on Stainless Steel 0.0105 (23)
2	5	$\frac{hD}{k_L} = 0.225\left[\frac{D\phi}{\lambda \mu_L}\right]^{0.69}\left[\frac{PD}{\sigma}\right]^{0.31}\left[\frac{\varrho_L}{\varrho_V} - 1\right]^{0.33}\left[\frac{C_L \mu_L}{k_L}\right]^{0.69}$	
3	6	$\left[\frac{C_{L\varrho L}\sqrt{\Pi a_L \phi}}{k_L \lambda \varrho_V}\right]\left[\frac{2\sigma}{\Delta P}\right]^{1/2}\left[\frac{\varrho_L}{g_c \Delta P}\right]^{1/4} = 0.0015\left[\frac{\varrho_L}{\mu_L}\left(\frac{C_{L\varrho L}\Delta T \Pi a_L}{\lambda \varrho_V}\right)^2\right]^{0.69}\left[\frac{C_L \mu_L}{k_L}\right]^{0.33}$	
4	2	(I) $\phi = C_l \frac{k}{2\sigma}\Delta P_s \Delta T_s\left[\frac{\varrho_L}{\mu}A^2\right]^{1/3}\left(N_{pr}\right)^{1/3}$ $A = \frac{c_{\varrho L} T_s \sqrt{\Pi a}}{(\lambda \varrho_V)^2 J}\Delta P_s$ (II) $\phi = 4.3\times10^{-5}\frac{\alpha C_{\varrho L} T_s}{\sigma^{1/2}(\lambda \varrho_V)^{3/2}}\left[c T_s a^{1/2}\right]^{1/4}\left[\frac{\varrho_L}{\mu}\right]^{3/8}\left[N_{pr}\right]^{1/3}\Delta P_s^2$	Combination / C_l: Water on Stainless Steel .. 0.7×10^{-3} (2); Diphenyl on Stainless Steel .. 1.2×10^{-3} (22); Meta-terphenyl on Stainless Steel 2.78×10^{-3} (22)
		Boiling in Heated Channel Flow:	
5	7	$\phi = 0.074\,\Delta T_{sat}^{2.84}$	Subcooled Water 30-90 p.s.i.a.
6	8	$\Delta T_{sat} = \frac{60\,(\phi\times10^{-6})^{1/4}}{e^{P/900}}$	Subcooled Water 500—2,000 p.s.i.a.

The principal correlations developed from the hypotheses listed above and applicable to pool boiling conditions are those due to Rohsenow[4], Forster and Zuber[5], and Forster and Greif[2] (see Table 1) of whom the last submit a very convincing case for hypothesis (4) which satisfies objections raised against the other hypotheses.

The Rohsenow correlation has met with considerable support and application with a wide range of liquids.[22, 23, 47] Those due to Forster and Greif are more recent but are also well supported.[2 22] In the Rohsenow and F. and G. correlations there is a constant to be evaluated experimentally which varies with the liquid-surface combination. It is also necessary in the relationships of Table 1 to insert a value for the surface tension and this is not available for many liquids at the temperatures concerned. Linear extrapolation from values given in the International Critical Tables is often employed but is open to question.

The application of correlations derived from or supported by pool boiling data to the case of boiling in forced flow in vertical heated channels has not been very successful. Early experiments on forced flow nucleate boiling in heated tubes or annuli established a correlation of the form: $\Delta T_{we} = \phi\, P^{-n}$.

i.e., as the pressure increases, the temperature potential required to transmit a given heat flux decreases. This marked effect of pressure had been noted also in pool boiling. In the nuclear reactor, we have induced or forced circulation of liquid over fuel elements in channels of circular or rectangular cross-section. Here we are concerned with local boiling and net steam generation in the channels and with the avoidance of burn-out. It has been necessary for reactor designers to proceed without the aid of a general equation for nucleate boiling and DNB limit, and hence their preoccupation has been largely with the procurement of empirical equations based on data obtained from test loops simulating reactor channel conditions, particularly with regard to pressure.

Under this incentive, Jens and Lottes[8] correlated data obtained at U.C.L.A., M.I.T. and Purdue, on nucleate boiling of subcooled water in forced circulation through electrically heated nickel and stainless steel tubes. The pressures ranged from 500 to 2,000 p.s.i.a. and the data were correlated to $\pm$ 14°F, by their equation (6) in Table 1. Other equations for heat transmission rates in the nucleate boiling regime in forced flow have been proposed, but the one quoted has found the widest recognition.

Aqueous solutions of salts, or organic liquids, usually exhibit lower boiling heat transfer coefficients than water at the same pressure, ΔT, or flux. At atmospheric pressure and $\Delta T = 10$°C, for instance, the coefficient for water will be 2,000 CHU/ft²h°C or better, while that for organic liquids will fall in the range 50 to 200 in the same units. Some experimental results for polyphenyls in nucleate pool boiling at atmospheric pressure are shown in Fig. 4.

Transition to Film Boiling and Burn-out

Of paramount concern to reactor designers is the avoidance of fuel element burn-out. Here, again, the main effort has been directed towards furnishing designers with some guidance, albeit empirical, under the specific conditions concerning them. Hence, the bulk of the studies on burn-out in heated channels has been directed to the pressure range of the PWR (2,000 p.s.i.a.), and the BWR (1,000 p.s.i.a.). The resultant equations will be discussed later.

As previously remarked, once the DNB point is reached, the transition from nucleate to film boiling occurs very rapidly, and burn-out follows. For this reason, the DNB flux is regarded as the burn-out flux for reactor design purposes. It is also easier to define the DNB flux in experiments. This has led to the use of the term burn-out synonymously with DNB in reactor engineering circles; it is so used in the equations in Table 2.

The understanding of the transition to film boiling is dependent on a sound understanding of the boiling mechanism. Nevertheless, it has been verified visually that at

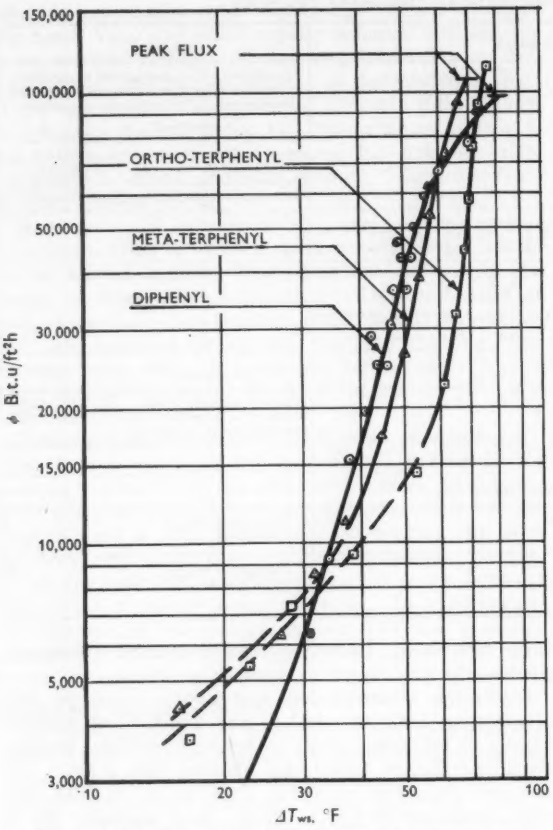


Fig. 4.—Heat flux v. ΔT_{sat} for polyphenyls in nucleate pool boiling at atmospheric pressure[22].

DNB, the vapour bubbles coalesce and blanket the heating surface with an unstable film. It has been noted by observers in the U.S.A.[39] and U.S.S.R.[40] that two factors influence the mechanism of vapour formation. These are the bubble population and the frequency of breakaway or speed of bubble growth. An increase in pressure produces a sharp increase in bubble population and only a comparatively slight increase in rate of bubble breakaway. This provides an explanation for the more rapid transition from nucleate to film boiling at higher pressures.

Important contributions to the analysis of the point of departure from nucleate boiling have been made in both the U.S.A. and U.S.S.R., and more recently, Zuber[39] has proposed a model which reduces the problem to one of the stability of a plane vortex sheet separating two phases in relative motion. The interface, the motion of which comprises two sets of superimposed stationary vibrations, takes the form of alternating spikes of liquid and bubbles. The idea of the instability of the film following some kind of wave motion is supported by observation.[38] Other theories have been suggested[21, 37] but Zuber[39] has formulated his with encouraging success. However, the analytical determination of the DNB flux for channel flow is still awaited.

The first experiments on burn-out, as with boiling heat transfer, were carried out under pool boiling conditions. Again, in the present state of knowledge, it has not appeared feasible to relate results derived in this way to boiling in heated channels. Krieth and Summerfield[42] were probably the first to study burn-out phenomena in heated channel flow.

Between 1949 and 1951, three significant contributions were made. These were the subcooled* burn-out correlations 7, 8, and 9 in Table 2. The next substantial contribution was the correlation, by Jens and Lottes, of data produced at U.C.L.A., M.I.T. and Purdue (equation 10), which provided a basis for the early design equations developed at Bettis for use in pressurized water reactors, operating at pressures in the region of 2,000 p.s.i. Bernath developed a burn-out correlation from the same and other data.[26] Then followed several notable contributions[12, 24, 27] but none of these has proved entirely satisfactory over a wide range of parameters. Experimental work at Bettis has been devoted mainly to conditions at a pressure of 2,000 p.s.i.a., and with the aid of this and previous work, from all sources, more refined burn-out correlations have been developed by Bettis for round and rectangular channels at this pressure (13). KAPL, using the same data as Bettis, arrived at a similar correlation for rectangular channels which eliminates the point of discontinuity occurring in the latter at the mass velocity of 1.6×10^6 lb/ft²h (14).

Subcooled burn-out studies in the U.S.S.R.[34] have been conducted on chrome-nickel steel tubes (8 mm i.d.), resistance heated, at pressures from 300 to 3,000 p.s.i.a., and quality burn-out data published[41] at 2,000 p.s.i.a. An unexplained difference of a factor of two in absolute value of burn-out flux appears between the U.S. and U.S.S.R. values.

The earliest work on quality burn-out was carried out on a very limited scale.[8] Insufficient data were obtained to form a basis for a satisfactory correlation. Some unexpectedly high heat fluxes were achieved, however, and these excited attention: 3×10^6 B.t.u./ft²h at 280 p.s.i.a. with 31% exit quality was one of the highest. Quality burn-out information was essential for the thermal design of BWR cores and considerable research was carried out at A.N.L., Hanford, KAPL and by G.E.C. Atomic Equipment Division[35, 36] which helped provide a basis for design.

Equations 13, 14 and 15 (Table 2) are developed upon the important observation[14] that the DNB flux is primarily dependent on the enthalpy of the coolant at the point of burn-out, defined as in the nomenclature. These equations are applicable, within the limits stated, to both subcooled and quality conditions of the bulk coolant.

Of reactor liquid coolants other than water, the polyphenyls are the most likely to be used with some measure of local boiling. While a great deal of boiling heat transfer research has been carried out on organic liquids generally, that applied to the polyphenyls is comparatively slight and restricted to pool boiling. For burn-out in forced flow, the most important contribution, so far, is equation 18. In comparing[20] the burn-out heat flux limits predicted for organically cooled reactors with those for non-boiling water-cooled reactors, under their respective characteristic operating conditions, it is found that the water-cooled reactor has a decided advantage in this respect of the order of sevenfold. It is found, too, that the presence of small concentrations of water in polyphenyl coolants can produce a marked lowering of the boiling point and hence of the DNB flux.

Influences on Burn-out

At the present stage of work on burn-out in forced flow in heated channels, it is not admissible to be emphatic about the relative influences of all variables under all conditions. It is evident, however, that the burn-out flux

* It is convenient at the present stage of knowledge to distinguish between burn-out when $T_b < T_{sat}$ ("subcooled" B.O.) and when there is net steam generation ("quality" B.O.).

for a given liquid is dependent to varying degrees on many factors, of which the most important are: Pressure, local bulk subcooling or quality, channel geometry, and mass velocity. It is convenient to remark on these parameters separately.

Influence of Pressure: In the subcooled region ($T_b < T_s$) the DNB flux decreases as the pressure increases. This is confirmed[8, 14] for the pressure range 500-2,000 p.s.i.a. There are indications that the effect of pressure on DNB is not so marked outside this range. Russian observers report[34] negligible influence of pressure between 300 and 600 p.s.i. and a decrease of DNB flux by a factor of four or five as the pressure increases from 600 to 3,000 p.s.i., although there is a marked difference in the reported flux levels in comparison with those current in the U.S.A.

In the quality region ($T_b = T_s$, i.e., net steam generation) the DNB flux also decreases with increasing pressure over the range 1,000 to 3,000 p.s.i.[17] There are indications that there is a maximum DNB flux in this case in the vicinity of 1,200 p.s.i. of magnitude about 20% greater than that observed in the region of 600 and 2,000 p.s.i. Outside this range, the variation of DNB flux with pressure is not marked[14, 17, 44] It has also been demonstrated that the attainable steam quality increases with pressure. Fig. 5 shows this in the results of an early investigation in the low pressure range.

TABLE 2. BURN-OUT CORRELATIONS

EQUn.	Ref.	Burn-out Correlation*	Range of application	Geometry	Remarks
7	9	$\phi_{BO} = (400{,}000 + 4{,}800\ \Delta T_{sub})\ U_b^{1/3}$	$P = 30-90$ p.s.i.a. $\Delta T_{sub} = 20°F-100°F$ $U_b = 1-12$ ft/sec	Annulus with central electrically heated S.S. tube. Dia.: 0.77, 0.73, 0.43 in.	—
8	10	$\phi_{BO} = 520\ G^{0.5}\ \Delta T_{sub}^{0.2}$	$P = 500-2{,}000$ p.s.i.a. $\Delta T_{sub} = 3-180°F$ $G = 1-8\times10^6$ B.t.u./ft² h	½ in. dia. tube (304 S.S.).	—
9	11	$\phi_{BO} = 7{,}000\ U_b^{0.3}\ \Delta T_{sub}$	$P =$ Atm. $\Delta T_{sub} = 20-28°F$ $U_b = 5-40$ ft/sec	¼ in. wide heated metal strip suspended lengthwise in middle of $\frac{1}{16}$ in. × ½ in. × 6 in. channel.	—
10	8, 14	$\frac{\phi_{BO}}{10^6} = K\left(\frac{G}{10^6}\right)^n (\Delta T_{sub})^{0.22}$ P 500 1,000 2,000 K 0.817 0.626 0.445 n 0.16 0.275 0.5	$P = 500-2{,}000$ p.s.i.a. $G = 0.96-7.79\times10^6$ $\Delta T_{sub} > 3°F$	Round tubes.	Data from U.C.L.A.*. Round tubes 0.226 in. I.D. × 24.6 in. 347 S.S.
11	12, 14	$\phi_{BO} = f\left(\frac{P}{P_c}\right) \cdot \varrho_g (H_g - H_b)(F)(J_1)$ $(F) = 1 + 10^{-4}(U_b D J_2) + 0.014[J_3(T_s - T_b)] + 0.5\times10^{-3}[(U_b D J_2)\ J_3(T_s - T_b)]^{1.78}$ (see references 12, 14 for definition of symbols)	$P =$ Atm.$-3{,}000$ p.s.i.a. $U_b = 0-110$ ft/sec $\phi = 0.075-11.4\times10^6$ $\Delta T_{sub} < 280°F$ Exit quality $< 70\%$	Unrestricted. (Data from round tubes.)	Data from refs. 8, 24, 25. Relation developed from an existing pool boiling correlation for sat. liquids. Accuracy $\simeq \pm 33\%$.
12	13, 14	P.C. Units. $\phi_{BO} = h_{BO}\ (T_w - T_b)_{BO}$ $h_{BO} = 5{,}710\left(\frac{\pi D}{D_i}\right)^{0.4} + 48\ \frac{U_b}{D^{0.4}}$ $(T_w)_{BO} = 57\ ln\ P - 54\left(\frac{P}{P+15}\right) - \frac{U_b}{4(D\pi/D_i)^{0.4}}$	$P = 500-3{,}000$ p.s.i. Vel. $= 4.5-54$ ft/sec $\phi = 0.5-2.3\times10^6$ Subcooled at exit.	Unrestricted. (Data from round tubes.)	Tested with data from round tubes. Refs.: 8, 26. Accuracy $= \pm 17\%$.
13	14	(a) $\frac{\phi_{BO}}{10^6} = 0.28\left(\frac{H_{BO}}{10^3}\right)^{-2.5}\left(1+\frac{G}{10^7}\right)^2 \cdot e^{-0.0012\ L/D}$ (b) $\frac{\phi_{BO}}{10^6} = 0.50\left(\frac{H_{BO}}{10^3}\right)^{-2.5} e^{-0.0012\ L/S}$ (c) $\frac{\phi_{BO}}{10^6} = 0.37\left(\frac{H_{BO}}{10^3}\right)^{-2.5}\left(1+\frac{G}{10^7}\right)^2 \cdot e^{-0.0012\ L/S}$ (d) $\frac{\phi_{BO}}{10^6} = 0.325\ F_p\left(\frac{H_{BO}}{10^3}\right)^{-2.5} e^{-0.0012\ L/S}$ $F_p = 1$ at 1,850–2,000 p.s.i. and 600–800 p.s.i. $= 1.2$ at 1,200 p.s.i., and linear variation with pressure between these limits. (e) $\frac{\phi_{BO}}{10^6} = 0.89\left(\frac{H_{BO}}{10^3}\right)^{-0.72} e^{-0.0012\ L/S}$	$0.2 \le \left(\frac{G}{10^6}\right) \le 8.0$ $0.2 \le \left(\frac{G}{10^6}\right) \le 1.6$ $1.6 \le \left(\frac{G}{10^6}\right) \le 5$ $P = 1{,}850-2{,}150$ p.s.i. $H_{BO} = 500-1{,}000$ B.t.u./lb Suggested conservative correlation for pressures other than 2,000 p.s.i.a. $P = 600-1{,}850$ p.s.i. $\left(\frac{G}{10^6}\right) \ge 0.2$ $H_{BO} = 600-1{,}000$ B.t.u./lb $H_{BO} < 600$ B.t.u./lb P and G as for (d)	Round tubes. Rectangular channels. Rectangular channels. Rectangular channels. Rectangular channels.	Based upon data compiled from all U.S. sources, including extensive work at Bettis, prior to Oct. 1957. For shapes other than wide rectangular channels with aspect ratio >10. Eqn. (a) is recommended in absence of specific data. For round tubes use Eqn. (10). Use Eqn. (d) if it gives lower value of ϕ_{BO}.
14	15, 17	$\frac{\phi_{BO}}{10^6} = 0.447\left(\frac{H_{BO}}{10^3}\right)^{-2.38}\left[1+\left(\frac{G}{10^7}\right)^{0.906}\right] e^{-0.00093\ L/S}$	$0.2 \le \left(\frac{G}{10^6}\right) \le 5$	Rectangular channels.	Based on same data as Bettis equations and avoids discontinuity at $G = 1.6\times10^6$ lb/ft² h.
15	16, 17	$\phi_{BO} = aGb\left(\frac{H_g - H_{BO}}{10^3}\right)^{c'} G^f$ $a = 8.3$; $b = 1.0$; $c' = 0.0022$; $f = 0.5$ (For designs, $a = 4.52$ recommended.)	$P = 2{,}000$ p.s.i.a. $500 \le H_{BO} \le 1{,}000$ $0.2 \le \left(\frac{G}{10^6}\right) \le 5.0$	Rectangular channels.	Based on Bettis data.
16	18	$\phi_{BO} = 0.29[400{,}000 + 4{,}800\ \Delta T_{sub}]\ U_b^{1/3}$ [i.e. Eqn. (1) × 0.29]	$P = 60-140$ p.s.i.a. $\Delta T_{sub} = 90-200°F$ $U_b = 6-53$ ft/sec	Rectangular channels 0.1 in. × 2.5 in. length: 18 in. to 36 in.	Channels similar to MTR–ETR type fuel elements. Flow downwards.
17	19	P.C. units $\phi_{BO} = 266{,}000\ (1 + 0.0365\ U_b)\ (1 + 0.00914 T_s)(1 + 0.0131P)$	$P = 25-85$ p.s.i.a. $\Delta T_{sub} = 5-75°C$ (9–135°F) $\phi = 0.9-3.24\times10^6$ B.t.u./ft²h	Flat 2 in. × 19 in. strip. Tubes 0.5, 0.8 in. dia. × 24 in. length. $D = 0.21-0.46$ in.	Heating surface material 304 s.s. and 70–30 Cu-Ni.
18	20	(a) Diphenyl: $\phi_{BO} = 454\ \Delta T_{sub}\ U_b^{0.43} + 116{,}000$ (b) Santowax R: $\phi_{BO} = 552\ \Delta T_{sub}\ U_b^{2/3} + 152{,}000$	$P = 23-406$ p.s.i.a. $T_b = 510-831°F$ Vel. $= \frac{1}{2}-17$ ft/sec $\Delta T_{sub} = 0-328°F$ $P = 100$ p.s.i.a. $T_b = 595-771°F$ $V = 5-15$ ft/sec	Annulus formed by heated tube ½ in. o.d., 0.02 in. wall with co-axial unheated rod 0.188 in. o.d.	The effect of geometry was not investigated, only a single test section being used.

* Liquid—water unless otherwise stated.

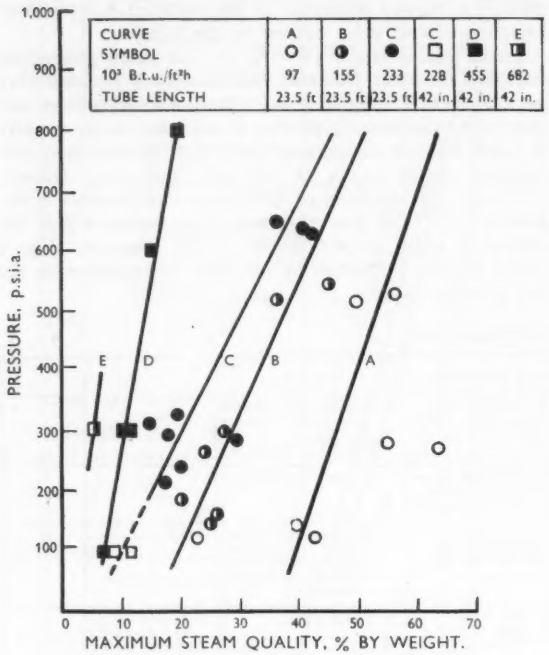


Fig. 5.—Maximum steam quality attainable without burn-out against pressure at the end of the heated section.

It is relevant to recall that in saturated pool boiling, it has been noted[45] that the DNB flux reaches a peak, generally in the region of one-third of the critical pressure, varying with the liquid, and extrapolating approximately to zero at both zero pressure and the critical pressure.

Subcooling or Quality: It has been observed[8, 14] that other conditions being constant, the DNB flux decreases as the channel inlet or outlet subcooling is decreased and continues to decrease as net steam is produced. The influence of pressures on these effects has been discussed above. In recent correlations, subcooling and condition effects are taken into account through the observed relationship of the local enthalpy value and DNB flux.

Effect of Channel Geometry: Channel size and geometry have an influence on DNB flux. It was originally suspected that the dependence was upon the L/D ratio[8, 14, 46] the DNB flux decreasing with increasing L/D, but recent tests at A.N.L. are claimed to indicate not only that the dependence is upon the diameter or equivalent diameter but that it is in the contrary sense. That is, that the DNB flux decreases as the diameter decreases. This subject will receive some scrutiny in the months ahead. It has been considered for some time[14] that the L/D parameter could not completely account for the effect of channel geometry on DNB flux.

Mass Velocity: The specific influence of mass velocity on the DNB flux has not been very adequately divined. At 2,000 p.s.i. Bettis[14] reported that the DNB flux increased slightly with increasing mass velocity, and also that there seemed to be a lower limit of mass velocity below which there was no influence on DNB. The lower limit at 2,000 p.s.i. being 1.6×10^6 lb/ft²h. More recent information[17] reveals, in the region of this pressure at any rate, that there is a reversal of the dependency of DNB flux on mass velocity as a quality condition is approached. This effect is illustrated in Figs. 6 and 7.

Other Influences: Of physical factors, other than those discussed above, which may be suspected to have an influence on burn-out flux levels, perhaps the most important are: nature of surface, dissolved gas, channel orientation, direction of flow and additives. It has been shown that the nature of the heating surface, its material and its roughness, has an influence on the position of the boiling curve in pool boiling. An increase in surface roughness due to scale formation or manufacture moves the curve bodily to the left. It has also been noted[43] in pool boiling that the effect of surface roughness is associated with the presence of adsorbed gas in the liquid, disappearing with the absence of gas. The material of the heating surface also has an influence. With regard to burn-out in pool boiling, Ellion[51] found that dissolved air produced a marked reduction of the burn-out heat flux.

With heated channel flow, the effect of nature of heating surface is not fully investigated. In tests at 2,000 p.s.i. on rectangular channels, Bettis[14, 48] concluded that the material or roughness up to 120μin. did not affect the DNB flux. The materials investigated were: nickel, zirconium-2 and stainless steel type 304. A recent report[49] on work currently in progress on this subject reveals that surface roughness permits substantial increases (up to 60% depending on style) in the DNB flux, with negligible influence on pumping power, at pressures in the region of 50 p.s.i. A summary of the results will be found in reference 50. Also reference 52 reports marked influence of surface condition on burn-out flux in high flux boiling experiments on metal plates heated by electron bombardment in an electron accelerator. So the work proceeds.

No significant effect of dissolved gas on burn-out in heated channel flow in the pressure range 500 to 2,000 p.s.i. has been observed[8, 53] and water with other additives has not been studied in relation to burn-out in heated channels, although it has been shown in pool boiling that DNB varies directly with the surface tension of the liquid. Some work on binary mixtures of organic liquids has been reported[45, 54] and it appears[54] that, at least in a certain pressure range, and in pool boiling, the transition from nucleate to film boiling in such a system is smooth, with no maxima at DNB.

TABLE 3.

TYPICAL VALUES OF HEAT FLUX

	Heat Flux, B.t.u./ft²h
Maximum direct solar heat flux at the earth's surface	300
Process industry heat exchangers	500 to 50,000
Modern Steam generator with combustion heating	0.1×10^6
Range of maximum core heat flux for 12 thermal nuclear reactors of various types	0.216–1.15×10^6
Dresden BWR (designed 1957) Maximum operating heat flux (corresponding max. fuel temp.=4,500°F: Limit=5,000°F)	0.346×10^6
Predicted burn-out limit at same location	0.8×10^6 (approx.)
Shippingport PWR (designed 1957). Maximum operating heat flux (U^{235}-Zirc. fuel) (max. cladding temp.=740°F)	0.418×10^6
Heat flux for centre melting of UO_2 fuel rod	0.5×10^6
Predicted burn-out limit at same location	0.7×10^6
Dounreay fast reactor, maximum core heat flux	3×10^6
Nozzle throat of operational liquid propellent rockets	3–5×10^6
Maximum expected at nozzle throats of rockets in near future	11×10^6
For satellite re-entry (approx.)	45×10^6

The bulk of heated channel boiling experiments have been carried out with a uniform flux distribution (except for possible end effects), and only in a few instances has a cosine distribution been attempted. Bettis[14] reports that a cosine axial heat flux distribution at 2,000 p.s.i.a. on rectangular channels produced no special effect on the value of the burn-out flux but that the location of the point of burn-out did not coincide with either the point of maximum flux or of maximum enthalpy. The same source reports that the inclination of the channel had no effect on the burn-out flux level except that burn-out always occurred with net steam generation, and the location of burn-out was on the upper side of the channel.

Influence of Spinning Flow: It is reported[55] that, for equal pumping power, spinning flow increases the DNB flux. The

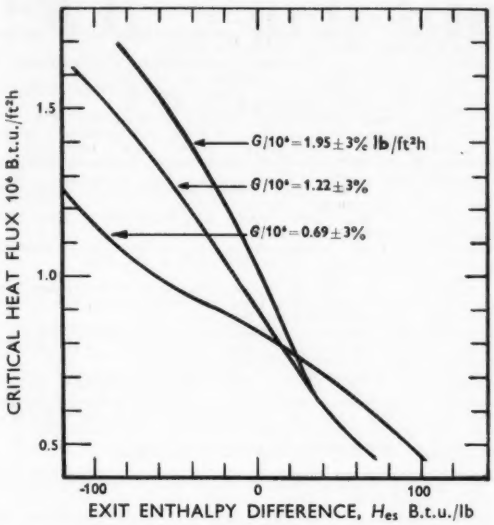


Fig. 6.—Effect of mass velocity on critical heat flux at 2,000 p.s.i.a. in a vertical channel (Tube, 304 s.s., 0.304 in. i.d. × 18 in.)[17].

advantage increases rapidly with pumping power. In one test run at 540 p.s.i. on an Inconel tube, 0.245 in. i.d., 0.9 in. heated length, exit subcooling 104°F, a burn-out flux of 35.1×10^6 B.t.u./ft²h was achieved. Of course, the pumping power required to achieve this (superficial axial velocity=48.9 ft/sec) would be prohibitive in a nuclear reactor. In any case, metallurgical considerations become important limiting factors at heat fluxes of this magnitude.

It is suggested that the mechanism which leads to the improved burn-out flux level in spinning flow in tubes, is the radial transport of hot liquid or vapour into the centre of the stream, but it is also argued[56] that this mechanism does not account for the movement of bubbles out of the heated peripheral region.

Future Developments

So far as the water moderated and cooled reactor is concerned, whether it be of the boiling or non-boiling variety, sufficient information is at present available to facilitate its design and safe operation within the pressure ranges and other conditions originally established in American practice, i.e., 2,000 p.s.i. for the PWR and 1,000 p.s.i. for the BWR. This is not to say that the optimum in the thermal design of these reactors has been achieved; much more knowledge of the boiling and burn-out process is required for this. At present, there are factors other than burn-out which limit the thermal performance of these reactors; but with improvements in fuel element design, materials and economics, there will come a desire to operate the reactor much closer to the burn-out limit. To this end, there is a pressing need to obtain further information on heat flux limits under transient conditions and with non-uniform axial and radial flux distributions, as well as on burn-out in reactor channels under natural circulation for emergency cooling.

Insufficient information is available for the determination of the optimum operating pressure of a given reactor system with respect to burn-out, and, associated with this, for the safe thermal design of water-cooled reactors at pressures other than those established at this time.

To solve these problems, there are two parallel and complementary courses being pursued. There are the dynamic or proof tests on loops to provide data on para-

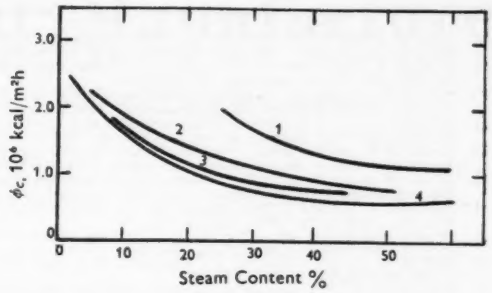


Fig. 7.—Variation of critical heat flux with quality and mass velocity of water-steam mixture[41]. Curve 1, $G = 368{,}000$ lb/ft²h; 2, $G = 736{,}000$; 3, $G = 1{,}104{,}000$; 4, $G = 1{,}472{,}000$ in the same units.

meter dependency which, as well as being of value to future analyses, lead to the development of empirical design equations of utility in the building of a given reactor. Then there are the analytical investigations of the boiling and burn-out mechanisms, greatly assisted by bench experiments of the pool boiling kind on bubble formation and population, etc., with increasing emphasis on transient phenomena. An important new tool in the pursuit of these studies is that of electroplating during boiling. By this means the bubble site population can be estimated from the number of pinholes left in the plating. This technique has been used with success[57] and a relation between heat flux and active site population proposed. Another tool could be that proposed[58] by which the hydrodynamic aspects of nucleate boiling are studied from the behaviour of air bubbled into water through a porous medium.

When the boiling and burn-out mechanisms are more fully understood and expressed in mathematical form, the proper interpretation of the data from loop tests will be facilitated and reliable correlation made possible. These remarks apply not only to water-cooled but to all liquid-cooled reactors. At this time local boiling in the organic cooled reactor is under consideration, but here decomposition of the liquid is an additional difficulty.

The next five years should see considerable progress and it would not be too much to expect an accepted unified relation, or something very close to it, for the boiling curve, within, say, 10 years.

REFERENCES

1. "Summary of Conference on Bubble Dynamics and Boiling Heat Transfer." Memo 20–137 Jet Prop. Lab. Calif. Inst. Tech., 1956.
2. Forster, K. E., and Greif, R., "Heat Transfer to a Boiling Liquid; Mechanism and Correlations." *Trans. Am. Soc. Mech. Engrs.* Ser. C. 81, 1, 43–53, 1959.
3. Gunther, F. C., and Kreith, F., "Photographic Study of Bubble Formation in Heat Transfer to Subcooled Water." Prog. Rept. No. 4–120, Jet Prop. Lab., Calif. Inst. Tech., March, 1950.
4. Rohsenow, W. M., *Trans. Am. Soc. Mech. Engrs.* 74, 969–976, 1952.
5. McNelly, M. J., *J. Imp. Coll. Chem. Eng. Soc.*, 7, 18–34, 1953.
6. Forster, H. K., and Zuber, N., *A.I.Ch.E. Journal*, 1, 531–5, 1955.
7. McAdams, W. H., *et al*; "Heat Transfer Rates to Water with Surface Boiling." AECU–200 (see also ref. 28).
8. Jens, W. H., and Lottes, P. A., "Analysis of Heat Transfer, Burn-out, Pressure Drop and Density Data for High Pressure Water." ANL–4627, 1951.
9. McAdams, W. H., *et al*, "Heat Transfer at High Rates to Water with Surface Boiling," *Ind. and Engrg. Chem.*, 41, 1945–53, 1949.
10. Buchberg, H., *et al*, Heat Transfer and Fluid Mech. Inst., 1951, Stanford University Press, Stanford, Calif., pp. 177–91.
11. Gunther, F. C., "Photographic Study of Surface-Boiling Heat Transfer to Water with Forced Convection," *A.S.M.E. Trans.*, 73, 115–23, 1951.
12. Griffith, P., "The Correlation of Nucleate Boiling Burn-out Data," A.S.M.E. Paper No. 57–HT–21, April 23, 1957.
13. Bernath, L., "Prediction of Heat Transfer Burn-out," Heat Transfer Symposium, A.I.Ch.E. National Meeting, Louisville, Ky., March 20–23, 1955.
14. "Forced-Convection Heat Transfer Burn-out Studies for Water in Rectangular Channels and Round Tubes at Pressures above 500 p.s.i.a." Oct. 1958. WAPD–188 (Unclassified AEC Report).
15. Longo, J., "Summary of KAPL (DIG) Investigation of Burn-out During Period Feb. 19, 1958 Through May 6, 1958." KAPL–M–DIG–TD–1, May 14, 1958. (Unclassified AEC Report).
16. Bell, D. W., "Correlation of Burn-out Heat Flux at 2,000 p.s.i.a." Paper presented to Amer. Nuc. Soc., Gatlinburg, Tenn., June 1959.
17. Power Reactor Technology, 2, 4, (AEC Pubcn.) Sept. 1959.

(References continued overleaf)

HEAT TRANSMISSION WITH BOILING - - - *References (contd.)*

18. Levy, S., Fuller, R. A., Niemi, R. O., "Heat Transfer to Water in Thin Rectangular Channels." *Journal of Heat Transfer*, 81, 2, 129, May, 1959.
19. Mirshak, S., Durant, W. S., and Towell, R. H., "Heat Flux at Burn-out." DP–355, Feb. 1959 (Unclassified AEC Report).
20. Core, T. C., and Sato, K., "Determination of Burn-out Limits of Polyphenyl Coolants." IDO–28007, Feb. 1958. (Unclassified AEC Report).
21. Mueller, G. O., "A Review and Assessment of Boiling Heat Transfer and the Departure from Nucleate Boiling." KAPL–M–GOM–2. (1958).
22. Jordan, D. P., and Leppert, G.," Nucleate Boiling Characteristics of Organic Reactor Coolants." *Nuclear Science and Engrg.*, 5, 349–359, 1959.
23. Mesler, R. B., Banchero, J. T., "Effects of Superatmospheric Pressures on Nucleate Boiling of Organic Liquids." *A.I.Ch.E. Journal*, 4, 1, March 1958.
24. Reynolds, J. M., M.I.T. Tech. Report No. 10, NONR–1848(39), (D.S.R. Proj. No. 7–7673), July 1957. (See also ref. 14).
25. Weatherhead, R. J., and Lottes, P. A. "Boiling Burn-out Newsletter No. 1." Brookhaven National Lab., Dec. 1954.
26. McGill, H. L., and Sibbitt, W. L., ANL–4603, Pt. 1, Feb. 1951. (AEC Unclassified Report).
27. Sonnemann, G., "A Method of Correlating Burn-out Heat Flux Data." *Nuc. Sc. and Engrg.*, 5, 242–247, 1959.
28. Nucleate Boiling Literature Search MND–1062–1, 1958.
29. Munn, J. F., "Heat Transfer to Boiling Water Forced Through an Electrically Heated Tube." BNL–2446, Oct. 1954.
30. Sterman, L. S., "On the Theory of Heat Exchange on Boiling in Pipes." Heat Transfer (Boiling), AERE, lib. trans. 579.
31. Sarukhanian, G., "Heat Transfer on Evaporation," AEC Tech. Report 2063, 1953.
32. Menegus, R. L., "Burn-out of Heating Surfaces in Water." D.P.–363, May 1959. (Unclassified AEC Report).
33. Weatherhead, R. J., "Burn-out with Net Steam Generation in Vertical Round and Rectangular Channels at 2,000 p.s.i.a." ANL, Oct. 4, 1956.
34. Aladev, Dodonos and Udalov, "Burn-out Fluxes for Water Flowing in Tubes." *Atomnaya Energiya* 6, W1, 74, 1959. (See *Nucleonics* July 1959, p. 102).
35. Carbon, M. W., *et al*, "Steam Generation in a Reactor." A.I.Ch.E., Preprint 46, Nuclear Engrg. and Science Congress, Cleveland, Ohio, 1955.
36. Galson, A. E., Polomik, E. E., "Burn-out Data Applicable to Boiling Water Reactors." ANS Meeting, Pittsburgh, Pa. June 1957.
37. Zuber, N., Tribus, M., "Further Remarks on the Stability of Boiling Heat Transfer." Rept. 58–5, Dept. of Engrg., University of California at Los Angeles, Jan. 1958.
38. Westwater, J. W., and Santangelo, "Photographic Study of Boiling." Ind. and Eng. Chem. v. 47, 1955, p. 1605.
39. Zuber, N., "On the Stability of Boiling Heat Transfer." Trans. A.S.M.E n. 3, v. 80, April 1958.
40. Polozhii, S. V., "Liquid Boiling with Heat Supply through the Wall." U.S.S.R. (1955); AERE Lib. Trans. 814 (1959).
41. Dolezhal, N. A., *et al*; "Uranium-Graphite Reactor with Superheated H.P. Steam." A/conf. 15/P/2139 (U.S.S.R.—see ref. 17).
42. Krieth, F., and Summerfield, M., "Heat Transfer to Water at High Flux Densities." Trans. A.S.M.E. 71:805–15 (1949).
43. McAdams, "Heat Transmission." 3rd Ed., McGraw-Hill, 1954.
44. Troy, M., "Upflow Burn-out Data for Water in Rectangular Channels at Pressures from 600 to 1,860 p.s.i.a." WAPD–TH–321 Sept. 1957.
45. Cichelli, M. T., and Bonilla, C. F. "Heat Transfer to Liquids Boiling under Pressure." AICE Trans., 41:755–87 (1945).
46. Epstein, H. M., *et al*, "Heat Transfer and Burn-out to Water at High Subcritical Temperatures." BMI 1116 (1956).
47. Rohsenow, W. M., "Heat Transfer with Evaporation," Heat Transfer Symposium, Univ. of Mich. 1953.
48. Jacket, H. S., *et al*, "Investigation of Burn-out Heat Flux in Rectangular Channels at 2,000 p.s.i." Trans. ASME, 80, p. 391, 1958. (Also discussed in WAPD 188).
49. Durant, W. S., and Mirshak, S., "Roughening of Heat Transfer Surfaces as a Method of Increasing Heat Flux at Burn-out." Prog. Rep. 1, DP–380, July 1959. (Reviewed in Pwr, R. Tech. 3, 2. p. 39).
50. Power Reactor Technology (AEC Publication), 3, 2, March 1960.
51. Ellion, M. E., "Mechanism of Boiling Heat Transfer." Calif. Inst. Tech., Jet Prop. Lab. Memo No. 20–88, March 1954.
52. Taylor, C. E., and Steinhaus, J. F., "High Flux Boiling Heat Transfer from a Flat Plate." UCRL–5414, Nov. 1958. (See also P.R.T. 3, 2. Mar. 1960).
53. De Bortoli, R. A., and Masnovi, R., "Effect of Dissolved Hydrogen on Burn-out for Water Flowing Vertically Upward in Round Tubes at 2,000 p.s.i.a." WAPD–TH–318. April 1957. (See also WAPD 188).
54. Jens, W. H., and Leppert, G., *Journal Amer. Soc. Naval Engineers*, 67, 137, 1955.
55. Gambill, W. R., and Greene, N. D., "A Preliminary Study of Boiling Burn-out Heat Fluxes for Water in Vortex Flow." A.I.Ch.E. Preprint 29, Chicago, Aug. 1958.
56. Oppenheimer, E., "The Effect of Spinning Flow on Boiling Burn-out in Tubes." NDA 80–1, July 1957.
57. Gaertner, R. F., and Westwater, J. W., "Populations of Active Sites in Nucleate Boiling Heat Transfer." Storrs Heat Trans. Conf., Preprint 105 (1959).
58. Wallis, G. B., "The Analogy Between the Bubbling of Air into Water and Nucleate Boiling at Saturation Temp." AEE–W–R28, (HMSO).
59. Griffith, P., and Wallis, J. D., "The Role of Surface Conditions in Nucleate Boiling." Storrs Heat Trans. Conf. Preprint 106 (1959).

TRANSLATIONS

Transmission de chaleur avec ébullition (493)

Après avoir passé en revue les régimes de transfert de chaleur, les parametres principaux dépendant des quantités de chaleur échangées sont discutés. Les théories actuelles qui ont été developpées pour analyser le phénomene par le calcul sont passées en revue. Des tables ont été dressées pour les théories les plus utilisées.

La fabrication des éléments de combustible de réacteur à eau sous pression (501)

Les éléments de combustible du réacteur de la centrale nucléaire de Yankee (Yankee Atomic Power Station) sont composés de tubes d'acier inoxydable contenant des galets de dioyde d'uranium. Les méthodes de chargement et de scellement des tubes ainsi que l'assemblage des éléments est discuté en détail. Les techniques de brasage ont été abondamment utilisées non seulement pour les assemblages partiels et pour les structures complètes, mais également pour les raidisseurs et les diaphragmes intérieurs aux cellules de combustible.

Le centre nucléaire de Winfrith (509)

Au cours d'une série d'articles, le centre nucléaire de Winfrith avec ses principales installations, sont décrits. Des détails sont donnés en particulier sur les installations relatives à l'étude du graphite pour réacteur. Suit une description de NESTOR, un réacteur source ainsi qu'une appréciation plus générale du travail expérimental à prévoir dans un programme de recherches en physique des réacteurs.

Accélérateurs et radiographie (517)

On construit des caissons de réacteurs qui nécessitent des tôles de plus en plus épaisses qui doivent être inspectées à l'aide de méthodes non destructives. La radiographie à haute énergie concurrence de plus en plus le contrôle des défauts par rayons gamma. Dans ce but de nombreux appareils comportant des accélérateurs de particules ont été mis au point. L'examen de tôles épaisses de plusieurs centimètres est ainsi rendu possible.

Uebertragung der Wärme bei kochender Flüssigkeit. (493)

Die verschiedenen Arten der Uebertragung der Wärme beim Kochen werden kurz besprochen, und es werden dann die wesentlichen Faktoren behandelt, die durch den Grad der Wärmeubertragung beeinflusst werden. Die zur Zeit geltenden Theorien, die die mathematische Grundlage für das Phänomen bilden sollen, werden besprochen und die erfolgreichsten in Tabellenform zusammengefasst.

Fabrikation der Brennstoff-Elemente für einen Druckwasser-Reaktor. (501)

Die Brennstoff-Elemente für das Kernkraftwerk Yankee sind aus Zylindern aus rostfreiem Stahl zusammengesetzt, die Kügelchen aus Uranoxydul (UO_3) enthalten. Die Art der Einfüllung und des Verschliessens der Zylinder und ihr Zusammenbau zu Elementen wird im Einzelnen besprochen.

Die Kernkraft-Studienanlage Winfrith (509)

In einer Reihe von Aufsätzen über die Studienanlage der Atomic Energy Authority in Winfrith werden zunächst das Werk selber und die Einrichtungen besprochen, die dort vorgesehen werden und insbesondere diejenigen, die sich auf das Programm beziehen, das für das Studium der physikalischen Grundlagen des Graphit-Reaktors aufgestellt ist. Es folgt dann eine Diskussion des Studien-Reaktors NESTOR und eine allgemeinere Bewertung der experimentellen Arbeiten, die zur Durchführung des Programms für das Studium der Reaktor-Physik erforderlich sind.

Beschleuniger und die Radiographie. (517)

Die Notwendigkeit der Verwendung stärkerer Stahlplatten in den Hochdruckbehältern für Reaktoren hat das Problem der zerstörungsfreien Werkstoffprüfung in den Vordergrund gebracht. Radiographie mit Verwendung hoher Energiestrahlung ist im Wettbewerb mit Gammastrahlen-Radiographie, und eine Anzahl Maschinen sind entwickelt worden, die Teilchen-Beschleuniger benutzen und zur radiographischen Untersuchung von Stahl von einer Stärke von vielen cm dienen können.

Transmision de Calor Con Hervidura. (493)

Después de pasar revista a los régimenes de transferencia de calor hirviente, se discuten los parámetros afectados con las razones de transferencia de calor. Las teorías corrientes desarrolladas para proveer el fenómeno con una base matemática son pasados en revista, tabulándose las que más éxito han tenido.

Fabricacion de elementos de Combustible " PWR." (501)

Los elementos de combustible para la Central de Fuerza Atómica Yankee comprenden conjuntos fabricados de tubos de acero inoxidable conteniendo granos gordos de dióxido de uranio. El método de cargar, sellar los tubos y ensamblarlos en los elementos se discute en detalle. Se ha hecho uso extenso de las técnicas de ligar a soldadura fuerte, no solo para las estructuras subasambladas y las completamente asambladas sino también para los atiesadores y separadores dentro de las mismas células de combustible.

El Establecimiento de Energía Atomica de Winfrith. (509)

Una serie de artículos relacionados con el establecimiento de la " AEA " en Winfrith discute primeramente el establecimiento y las facilidades que se están instalando y particularmente aquellos conjuntos que se relacionan con el programa de la fisica de reactores a grafito y esto va seguido de una discusión del reactor de fuente NESTOR y una apreciación más generalizada de las labores experimentales necesarias en un programa de la fisica de reactores.

Aceleradores y Radiografía. (517)

La necesidad de tenor acero más grueso en los recipientes de presión en reactores ha posado el problema del ensayado no destructivo; la radiografía de elevada energía es una competidora de la gamaradiografía en este sentido y se han evolucionado varias máquinas que emplean aceleradores.

PWR Fuel Element Manufacture

Techniques Evolved by Westinghouse

Extensive use has been made of braze-bonded techniques for positively locating groups of UO_2 pellets in the stainless-steel cans and for building up rods into complete fuel assemblies.

By M. D'AMORE

(Senior Metallurgist, Supervisor, Yankee Core Fabrication, Westinghouse, Atomic Power Department)

APPROXIMATELY 3,500,000 uranium dioxide ceramic pellets were used in fabricating the 23,142 fuel rods for the Yankee reactor core. The fuel rods are braze-bonded together with a series of spacer ferrules to form 684 sub-assemblies and these are made up in groups of nine into the 76 assemblies weighing 910 lb each which form the core structure. A fuel rod consists of a column of cylindrical uranium dioxide pellets contained, within a 93-in. long stainless-steel tube, interrupted at 15-in. intervals by stainless-steel discs joined to the inside of the tube.

Fuel

Using the ammonium diuranate process, the uranium dioxide powder was precipitated from UF_6 gas with a U^{235} content of 3.4% obtained from the gaseous diffusion plants of the U.S. AEC at Oak Ridge. The Mallinckrodt Nuclear Corporation and the Nuclear Materials and Equipment Corporation converted the UF_6 gas to uranium dioxide powder, and the final pellets were produced by Mallinckrodt and by the Westinghouse Blairsville Plant.

Tolerance limits for the pellets were:

Length:	0.600 in. ± 0.050 in.
Diameter:	0.294 in. ± 0.0005 in.
Weight of Pellets:	11.15–11.59 g/in. length

The large quantity of pellets which Westinghouse A.P.D. received from the two suppliers precluded individual inspection and a sampling plan was devised for accepting or rejecting pellets on a batch basis. The quality level of this sampling plan ensured that 95% of the batches accepted would have no greater than three defects per 100. Each pellet in a sample batch was tested for conformance with length, diameter, density and chipping specifications. Chemical analyses for total uranium, O/U ratio, carbon, U^{235} and 27 impurity elements were performed periodically.

Nearly all pellet batches met density specification and a similar experience was had with length, diameter, chipping and chemical content measurements. Density specifications for the UO_2 pellets were in terms of weight per unit length rather than weight per unit volume as the pellet diameters were substantially constant. Inspection calculations were thereby simplified for pellet vendors and the Atomic Power Department Inspection Group who used this method of density specification.

Fuel Rods

The Yankee reactor fuel rod design is shown in Fig. 1. Approximately 150 uranium dioxide pellets are contained in each type 348 stainless-steel tube which is 93 in. long, 0.298 in. I.D., with a 0.021 in. tube wall thickness. The pellet stack is interrupted at about 15-in. intervals by a stainless-steel disc locked in position by crimping the fuel tube into a groove around the periphery of the disc. Stainless-steel end plugs are pressed and welded in each end, sealing the tube after loading. The method of loading a fuel tube is illustrated in Fig. 2. A disc, located near one end is crimped in position and 25 UO_2 pellets are then inserted by sliding the tube over a stainless-steel ram. The tip of the ram extends through a central hole in the disc, fixing the axial gap distance required in each compartment for differential expansion between pellets and tube during reactor operation. External dies crimp the tube on to the disc after contact is established between the pellet column and the prepositioned disc. Each disc is plated with a 0.0009-0.0012 in. thickness of nickel-phosphorus braze alloy prior to loading of the tubes, the actual brazing taking place during the cycle in which fuel rods are joined into sub-assemblies.

The brazing improves heat transfer between discs and tubes and provides additional support for the tube at the

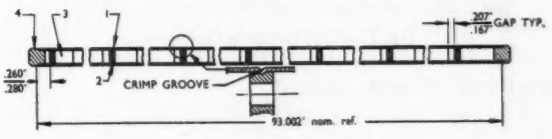


Fig. 1.—Fuel rod.

crimped region. The central hole through the disc permits equalization of fission gas pressure along the fuel tube length during the life of the element.

A vacuum system attached to the fuel tube end containing the prepositioned disc relieves back pressure from compression of air as the pellets are slid into the fuel tube, permitting a faster loading rate. The fuel pellets are loaded into short fuel tube sections (transfer tubes) prior to insertion into the fuel tube. These transfer tubes provide for uniform compartment lengths and permit the sorting out of oversize pellets before loading into the fuel tube. Chipped pellets are rejected by the transfer tube loading operator who visually examines each pellet. The two compressed air machines designed and constructed to aid in loading the fuel tubes have given loading rates of 100 fuel tubes per day per machine.

End Plug Weldments

The tungsten inert gas shielded arc welding process with no addition of filler material, was employed to weld the tube end plugs. The weld zone was rotated at a speed of 18 rev/min (=18 in./min) beneath a stationary heliarc torch using 12-13 V, 33-35 amp. Approximately 46,500 end closure weldments were produced in manufacturing the Yankee core fuel rods. Inspection by visual examination at 60× magnification, helium leak testing, and X-ray methods resulted in only 3.15% rejects, of which 1% were successfully repaired by re-welding, whilst an additional 1.8% were repaired by replacement of the end plug. Only 0.35% proved non-repairable.

To produce consistently sound welds of the thin-walled

tubing to the relatively massive end plugs it was necessary to keep a close watch on the following:

(1) End plug material composition selection to provide 4 to 10 ferrite content in the weld structure (based on the Schaeffler[1] structural diagram for stainless weld metal) to minimize weld cracking.

(2) Dimensional control of end plugs to ensure a good fit in the fuel tube.

(3) Careful squaring and de-burring of fuel tube ends.

(4) Exact alignment of end plug and tube during insertion of the end plug to avoid distortion of the tube end.

(5) Thorough cleaning of end plugs and tube ends.

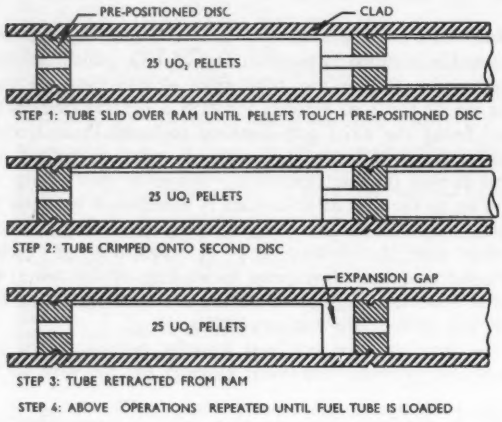

PRE-POSITIONED DISC
CLAD
25 UO_2 PELLETS
STEP 1: TUBE SLID OVER RAM UNTIL PELLETS TOUCH PRE-POSITIONED DISC
25 UO_2 PELLETS
STEP 2: TUBE CRIMPED ONTO SECOND DISC
EXPANSION GAP
25 UO_2 PELLETS
STEP 3: TUBE RETRACTED FROM RAM
STEP 4: ABOVE OPERATIONS REPEATED UNTIL FUEL TUBE IS LOADED

Fig. 2.—Tube crimping technique.

Fuel Rod Assembly Method

Fuel rods were joined into sub-assemblies using a high temperature braze bonding technique.[2] The fuel rods were accurately spaced and joined into a rigid assembly by brazing to ½-in. long ferrules (tube segments) positioned between the fuel rods as illustrated in Fig. 4. Ten different configurations of brazed sub-assemblies, each containing 25, 30, or 36 fuel rods, were produced and a total of 684 brazed units were manufactured to make the 76 fuel assemblies for the Yankee core. Eighteen additional units were required for two spare fuel assemblies.

For such a structure the strength of the brazed joints is a critical factor and extensive development work was required before the core manufacture could be started. A brazing alloy consisting of 90% nickel and 10% phosphorus was ultimately selected as a result of this work. Plating the ferrules with electroless Ni-P proved to be an ideal method of applying the brazing alloy as a uniform coating of nickel containing 8-10% phosphorus could thus be deposited on the ferrule and controlled to within ±0.0001 in. of the specified thickness. This ensures uniform, reproducible bonded joints.

Braze Bonding Technique

Nickel-base brazing alloys produce intrinsically brittle joints with conventional brazing methods. However, the technique developed by Westinghouse produces a high strength ductile joint. The technique depends upon intimate contact of the brazed parts to enhance the formation of a ductile single-phase bond between tube and ferrule. The single-phase bond is formed due to phosphorus depletion of the brazing alloy by diffusion of the phosphorus into the steel during the furnace brazing operation. A single-phase alloy forms at the point of contact when joining two stainless-steel tubes after five minutes heating at 1,850°F when using 0.0005 in. thick electroless

Fig. 3.—Loading fuel tubes.

Ni-P plating on one of the tubes. Isolated patches of eutectic still are present, but after 4 hours at 1,850°F the single-phase region increases.

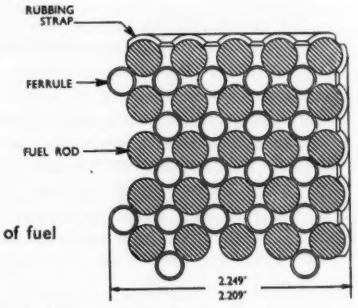
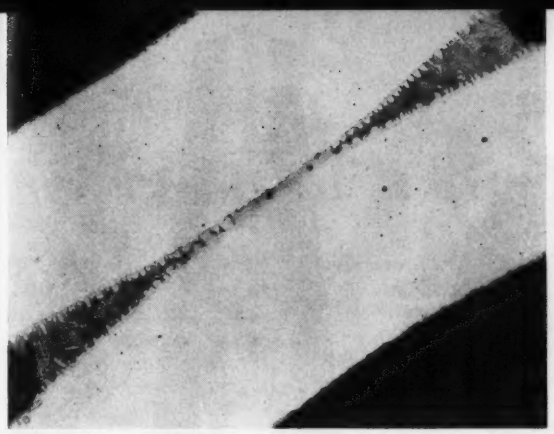


Fig. 4.—Cross-section of fuel sub-assembly.

The strength and ductility characteristics of the single-phase region of the braze point are similar to those of the base metal. It is possible to form joints with strength characteristics similar to that of the stainless-steel base metal by careful control of the amount of braze alloy, brazing temperature, brazing time and fit of the parts.

A survey of the effect of Ni-P plate thickness and brazing time was conducted to optimize conditions for manufacturing. Specimens were prepared using Ni-P plate thicknesses varying between 0.0005 in. and 0.0012 in. and brazed for one and three hours at 1,875°F. The brazed joints were fractured in tension using a tensile test machine, with results as tabulated in Table 1. The highest strength was obtained for joints produced with a 0.005 in. thickness of Ni-P plating. Joint strength decreases as plating thickness increases and is greater for a three-hour than for a one-hour brazing time. The results indicate that minimum thickness of braze plating produces stronger joints in a shorter time at temperature, as the separation



distance between fuel tube and ferrule is smaller and bond growth can progress more rapidly. Brazing for three hours at 1,875°F using a 0.0005-in.-0.0008-in. Ni-P plate thickness on all ferrules was finally specified for fabrication of the Yankee fuel rod sub-assemblies.

TABLE 1.
Effect of plate thickness and brazing time variations on strength of Ni-P brazed joints

Ni-P Plate Thickness, in.	Brazing Conditions	Number of Joints fractured	Average Tensile Strength, p.s.i.*
0.0005	1,875°F – 1h	85	36,000
0.00075	1,875°F – 1h	73	37,600
0.0012	1,875°F – 1h	62	25,200
0.0005	1,875°F – 3h	40	45,000
0.00075	1,875°F – 3h	70	39,500
0.0010	1,875°F – 3h	77	28,700

* Based on 0.010 in.² braze bond area.

Brazing Procedures

Brazing fixtures were designed and procedures developed for commercial production of the fuel-rod sub-assemblies. Prototype brazing studies indicated that sub-assemblies 95 in. in length could be brazed in either a vertical or horizontal position to specified tolerances by the use of suitable fixtures. Vertical brazing was selected for manufacturing as the furnace could be positioned within an available pit, thus requiring less floor and overhead space. Furthermore, fixture designs were less complex for vertical operation and an overhead crane was available for moving the hot retorts from the furnace to the cooling rack.

Two " globar " type vertical pit furnaces capable of providing a 108 in. long uniform heat zone at 1,850°F, were installed for production runs. Retorts 12½ ft long, sealed at the bottom and equipped with removable tops were constructed from 6-in. o.d. seamless Inconel pipe to suspend and protect the sub-assemblies in the hot zone of the furnace during brazing. Four retorts were sufficient for 24-hour-a-day operation. Hydrogen from a central system was externally piped to these retorts through flexible metal lines, and piped internally to the bottom of the retort to provide a hydrogen atmosphere within the retort. Valves on the inlet and outlet lines permitted dew-point readings throughout the brazing cycles and a thermocouple well within the retort permitted temperature probes along the sub-assembly length while at temperature. Valves were installed in the removable retort top cover so that the retort could be sealed and the gas lines disconnected after brazing, thus permitting transfer of hot retorts to a cooling rack without contamination of the retort atmosphere. The retorts were purged before and after brazing with argon valved through the hydrogen inlet lines.

It was found that fixture design was extremely important in controlling fuel rod-to-ferrule fit, lateral dimensions and longitudinal straightness in the brazed sub-assemblies. A

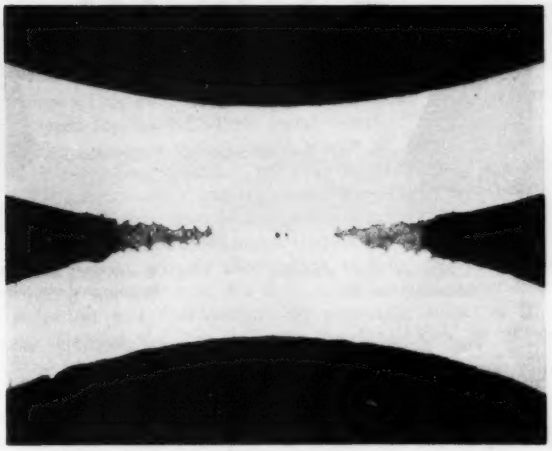


Fig. 5.—Braze-bonded S.S. tubes.
(a) (Left) Bond formed in 5 min. at 1,850°F. Top tube plated with 0.0005 in. of Ni-P. (b) (Above) Growth of bond region after 4 hours at 1,850°F.

successful fixture design must meet the following requirements:

(1) High temperature strength should be used in fixture components to minimize dimensional changes during the brazing cycle.

(2) Fixture expansion characteristics must be similar to those of the fuel rods to minimize distortion and ensure proper clamping at all temperatures.

(3) A balanced mass of metal around the axis of the fixture is required to prevent differential cooling which could result in longitudinal bowing of the vertically suspended assembly.

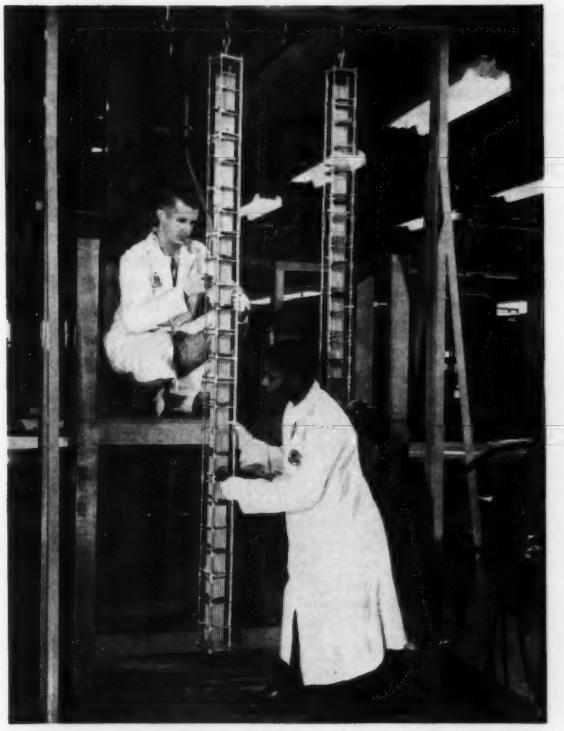


Fig. 6.—Preparing fuel sub-assembly for brazing.

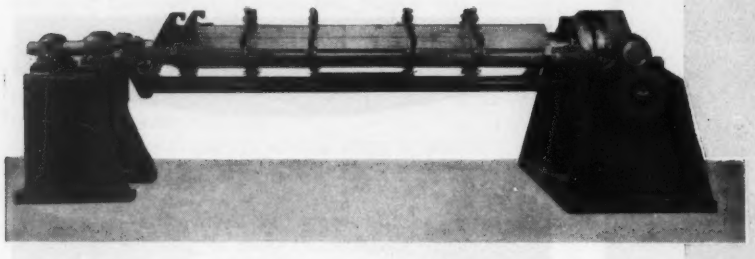


Fig. 7.—(Above) Fuel element assembly fixture.

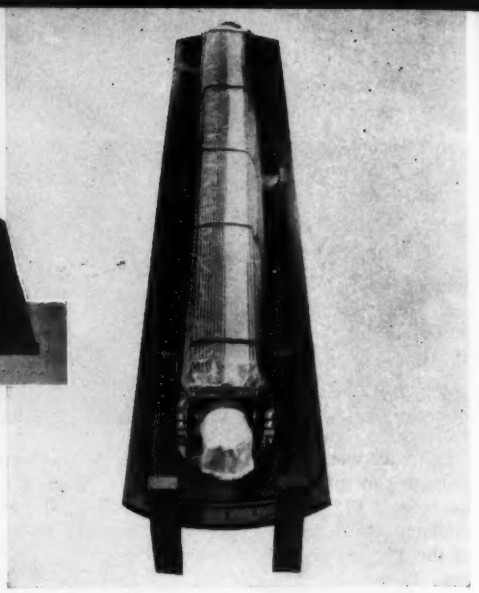


Fig. 9.—(Right) Fuel assembly in shipping container.

(4) The design must permit rapid assembly and disassembly.

(5) Fixtures must be reusable for a reasonable period.

The type of braze fixture developed for production brazing of the sub-assemblies (Fig. 6) consists of a series of clamps of $\frac{1}{8}$ in. thick type 347 stainless steel positioned by bushings and collars on four type 316 tie rods. Type 304 stainless steel end plates, $\frac{1}{2}$-in. thick, are used to align and support the tie rods. Two sides of the fixture can be opened after brazing to facilitate removal of the brazed sub-assembly. Bonding between fuel rods and fixture clamps is prevented by using titanium oxide coated shim stock between clamp and rod. Removable stainless steel spacer bars between fuel rod rows maintain design spacing during brazing. Slippage of ferrules during brazing is prevented by titanium oxide coated stainless steel wires which pass beneath the ferrule rows and fasten to the fixture clamps. The maximum life obtained from any fixture during manufacture of the core was 32 brazing cycles; however, average fixture life was limited to 15 brazing cycles.

Fuel Element Assembly

The fuel assemblies are produced by stacking nine brazed sub-assemblies in the assembly fixture and securing them by 12 separately adjustable pressure pads provided in four locations spaced along the assembly fixture length. The cross sectional size of the assembly is adjustable to specified limits using the pressure pads. The clamped dimensions of the fuel assembly are retained after removal from the fixture by the use of straps and ties.

One-inch wide stainless steel "rubbing" straps are brazed across the outer fuel rods during brazing of the sub-assemblies (Fig. 4) and are aligned with mating straps located on the opposite side of the fuel assembly. Stainless steel "tie" straps 0.030 in. by 0.500 in. wide, inserted through the fuel assembly between fuel rod rows, are subsequently welded at each end to the rubbing straps. This restrains movement of the sub-assemblies upon removal from the fixture.

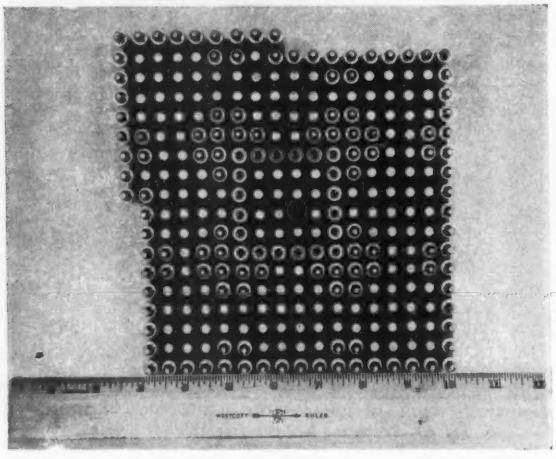
End plates are attached to each end of the element assembly, as shown in Figs. 8(a) and (b) before removal of the assembly from the fixture. The end plates are attached to the central sub-assembly only with stainless steel machine screws. The remaining sub-assemblies are secured to the end plates in a manner which allows a slight lateral movement of individual sub-assemblies and prevents thermal bowing of the entire assembly during operation. Bolting of a handling nozzle to each end plate completes the assembly operation.

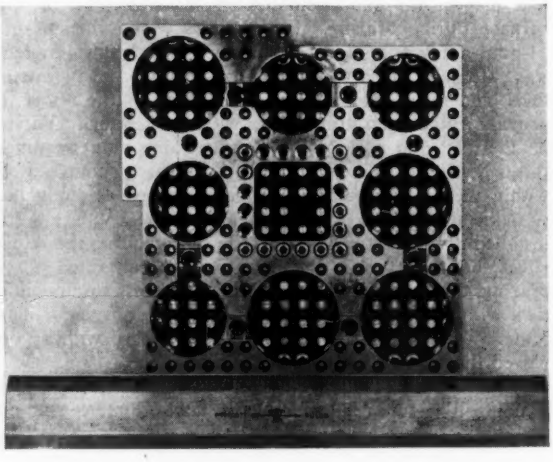
The completed fuel assembly is chemically cleaned and mechanically inspected after which it is sealed in a plastic bag and placed in a shock-absorbing hermetically sealed metal container (Fig. 9) for shipment to the reactor site.

BIBLIOGRAPHY

1. Thielsch, Helmut, "Physical Metallurgy of Austenitic Stainless Steels," *Welding Journal* 30,12, Research Supplement, 577-5S, to 621-S, 1950.
2. King, P. P., and McGeary, R. K., "Braze Bonding Stainless Steel Fuel Elements for Nuclear Reactor," *Welding Journal* 38,6, Research Supplement, 241-S to 246-S, 1959.
3. Patriarca, P., *et al.*, "Electroless-plated Brazing Alloys," ORNL-2243, 1957.
4. Antel, *et al.*, Pat. No. 2,795,040, issued June 11, 1957.

Fig. 8 (a)—(Left) Fuel assembly before attachment. (b)—(Below) After attachment.





Selection of a Reactor Neutron Source

A CONSIDERATION of the requirements of the various types of sub-critical experiments has shown the need for a neutron source reactor of 10kW(t) average power. The main limitations upon the reactor are that it should be reasonably compact so that its outer faces are similar in size to the smallest sub-critical experiments likely to be of interest, and any reflector surrounding the reactor core should be sufficiently thick to ensure negligible reactivity coupling between the core and the external experiments, but thin enough to ensure no serious loss of neutron output. The smallest exponential experiments presently envisaged are cubical with 3-4 ft sides, so a core of similar or smaller size would be appropriate.

For each neutron absorbed in the reactor core, k_∞ neutrons are produced and $(k_\infty - 1)$ leak from the core. Thus leakage flux is proportional to power and rises with increasing value of k_∞. As core materials with a high k_∞ value lead to a more compact reactor, it is evident that for a given power the maximum neutron leakage will be given by a compact core.

Cores which match these criteria are the BSR or LIDO, and the TRIGA pool-type reactors. Such cores give the advantages of a low critical mass (about 2-3 kg), easy fuel handling through the pool water and designs which are well established, and readily lend themselves to operation at higher powers if required. It is found by experiment that some 3 in. of water reflector around a LIDO-type core provides sufficient reflection to retain a small critical mass and sufficient reactivity decoupling for safety purposes whilst allowing adequate neutron transmission. The main disadvantage of the pool-type reactor is that a vertical neutron beam to a top experiment is not available directly from the core. Furthermore, a tall, fixed water tank is required and watertight aluminium neutron windows, double-walled for high integrity, are needed in the vicinity of the reactor core to allow the leakage neutrons to enter the experiments.

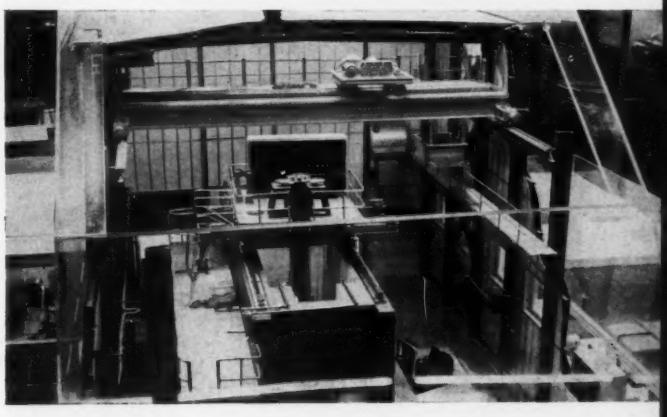
A pool reactor core can be readily mounted on a bridge-structure and made mobile, its water shield automatically adapting itself to changes in the core's position. This feature could be exploited to advantage by arranging two groups of three caves around each end of a long narrow pool. If some 20 ft of water together with external concrete shielding were provided between the two reactor positions, the reactor could be operated in one position whilst full access was available to the caves around the other position. There are several obvious variations to this general scheme but it soon becomes apparent that, as the total cost of the caves and ancillaries is several times the cost of the reactor core and its associated equipment, the emphasis must be upon high utilization of the caves as well as of the reactor.

The most obvious choice, therefore, is to arrange several caves around a fixed reactor core and to irradiate these to the maximum practicable extent. Between one and eight caves have been considered (e.g., the Babcock and Wilcox pool test reactor at Lynchburg has one cave only), but a good compromise is to use four caves in association with a four-sided reactor. Demountable rather than monolithic construction is to be preferred for the caves in order to provide the maximum flexibility to meet future changes in experimental requirements. High-density iron shot loaded concrete is desirable rather than ordinary concrete in order to facilitate access through the cave walls to the experiments. This cave layout and construction was therefore adopted for the NESTOR installation.

The four-cave arrangement would be quite practicable with a pool-type reactor, the core of which would simply be immersed in a tall square-section thimble-tube filled with water, that part of the thimble-tube surrounding the core being of double-skinned aluminium construction. The water would provide moderation and natural convection cooling together with the 3 in. layer around the core for reflection and decoupling. By providing some 20 ft of water above the core sufficient shielding would be present both for operation and for fuel handling during shut down. The water depth could be reduced to about 10 ft which is adequate for fuel handling, if it were supplemented by a removable concrete shield above the tank for use during operation.

If the external facilities are further redesigned so as to remove all the shielding water from above the core, installing in its place concrete shielding and appropriate fuel element handling devices, and if in addition a vertical graphite thermal column is inserted within the centre of the core, it becomes practicable to provide a vertical neutron beam whilst keeping a sufficient depth of reflector water (about 1 ft) immediately above the fuel elements. This is necessary to ensure that disturbances upon the free surface of the water cannot perturb the reactor operation. The consequent dispersal of the core so that it has a large internal neutron leakage increases the critical mass, and in the Argonaut or Jason core adopted for NESTOR, which has such an arrangement, the critical mass is some 4 kg of U^{235}. In a reactor of this type the hydrostatic pressure of water within the core tank is very low and the tank integrity correspondingly high. Furthermore, in the Argonaut-type reactor the reflector is made of graphite, thus providing a second partial barrier against the accidental leakage of water into the associated experiments. The 18-in. average reflector thickness required around a core already enlarged due to the 2-ft-diameter internal thermal column results in a rather large reactor side area (some 5 ft by 4 ft), but this is a convenient size for feeding graphite moderated sub-critical experiments. The internal thermal column provides a smaller area vertical beam neutron source appropriate to light hydrogen moderated experiments.

A model of the pool reactor LIDO at AERE, Harwell, primarily used for shielding experiments.



Efficient utilization of the caves also demands that the experiments should be capable of withdrawal and replacement as soon as possible after termination of an experiment. Withdrawal can be carried out only after about 48 hours, 16 hours, or a quarter of an hour following, respectively, irradiation at flux levels of 10^8, 10^7 or 10^6n/cm² sec. At one time consideration was given to an internal transport system to enable experiments to be transferred to shielded radioactivity-cooling positions. This would free the irradiation positions for further experiments, simultaneously avoiding the need for personnel access to the irradiation cave in order to change the experiment. Such a scheme proves very costly in shielding and equipment whilst also making it difficult to utilize all the reactor faces for irradiation positions. It turns out on balance to be more economical, and also more flexible, to use all the available reactor faces for irradiation purposes and to allow cooling to take place in the irradiation positions. The irradiation must be stopped for this purpose and this is readily achieved by polythene-cadmium neutron shutters. This neutron-absorbing material is combined with 8 in. of lead to facilitate personnel access to the caves in the face of core gamma emissions whilst the reactor is shut down.

The Design of NESTOR

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THE decision to build a neutron source reactor at Winfrith was taken in June, 1959, following which the designs were drawn up and a construction programme initiated. Contracts were placed with the Hawker Siddeley Nuclear Power Co. in November, 1959, for a modified Jason reactor and the following month with the Turriff Construction Corp. for the shielding. Most of the manufacture of reactor and shielding is now finished and completion is scheduled for the end of the year.

The subcritical assemblies to be driven by NESTOR are graphite moderated uranium or plutonium fuelled stacks of maximum size 6 ft cube, or light hydrogen moderated liquid assemblies, somewhat smaller, employing various fuels. The solid stacks may, in due course, be heated to 400°C, or even higher temperatures. The physics measurements to be carried out on the assemblies are fast fission factor, conversion factor, resonance escape probability, neutron spectrum and fine structure distribution. These measurements will be made by both foil irradiation and fission chamber techniques, these involving a variety of special access arrangements.

The reactor proper, with its reflector approximately 5 ft square in plan, is surrounded by four demountable caves measuring some 8 ft x 8 ft by 7 ft 6 in. deep inside, with sliding doors to close the entrances. Between the faces of the reflector and the caves are four remotely controlled shutters, to control the neutron leakage and to isolate the caves from shut down core gamma radiation.

NESTOR has an MTR type core forming an annulus, water being both moderator and coolant; cooling is by natural convection between the plates. The reflector is of graphite, and surrounds the annulus which is 6 in. wide, 2 ft 6 in. mean diameter and is formed by two concentric aluminium tanks.

Modifications to Jason

To satisfy the high utilization envisaged, it has been necessary to modify Jason to meet the requirement of continuous running at a power level of 10-kW. The majority of modifications incorporated are those necessary to meet the high availability (two shift working is proposed), and accommodate the new shield design. Hawker's have made similar changes also to their standard reactor.

The original loose plate fuel assemblies have been changed to 16 plate (brazed-type) elements of half the annulus width (there being a double row of fuel element positions), mainly to assist in the handling problem resulting from the fission product build-up. To elminate the possibility of corrosion between the graphite and the core components, the graphite blocks which take up unoccupied fuel element spaces, and the wedges (which form radial spacers between the elements and/or blocks) are being canned in aluminium. As the fuel elements and graphite blocks are similar dimensionally, it is still possible to load the fuel elements in a double row in the annulus (slab loading) although initially the fuel elements will be in the inner row of positions only (annular loading), the outer positions being filled with canned graphite blocks. The critical mass for the annular loading is expected to be about 4.2 kg of U^{235}. To give a smaller fuel increment during the approach to critical some elements with less than 16 plates containing fuel are provided, the remaining plates being of aluminium.

To facilitate the handling of irradiated fuel the shot loaded concrete plug above the core is arranged to rotate and is mounted on rollers. Two smaller plugs are positioned within it, one above each fuel element row, to provide a means of locating the flask over any fuel element. A handling flask, auxiliary shield door, and remote handling tool are available to transfer the fuel elements between the reactor and the nearby storage holes. Unfortunately complete unloading of the core will be necessary to carry out the changing of a control mechanism or any major maintenance on the shutters.

It has been necessary to raise the core centre line of the reactor by placing the graphite reflector on a plinth 2 ft high. Part of the sides of this concrete plinth and the graphite reflector have been faced with lead blocks, as has the top shield support structure, to assist in completing the shut down gamma shielding when the shutters are closed. Cadmium sheet has been used in various places to reduce activation from thermal neutrons.

There has been little change from the original Jason arrangement of the cooling system except for provision for changing the ion exchanger resins. The existing coolant flow of 3 gal/min is adequate, as short period operation at 10 kW was envisaged in the prototype Jason design. The system of moderator dumping, both as part of the reactor trip system and as a start up safeguard has been retained without change.

Control and Instrumentation

The original Jason control mechanisms have been slightly modified to reduce induced activation and radiation

damage. The four identical mechanisms (two safety rods, one fine rod and one coarse), which are situated at the top of the graphite reflector immediately outside the annulus, have been encased at the sides and beneath with 2 in. of lead and ¼ in. boral. Several materials within the gearbox and drive unit have been changed to be of lower activation cross section. As unloading the core will be a fairly lengthy operation, it is essential that any unplanned maintenance should be reduced to a minimum and hence one item of potential failure, the limit switches, have been duplicated and can be wired into circuit externally.

It was decided that Jason's existing instrumentation, whilst adequate for its original purpose, could not easily be adapted to meet the new operational requirements. An outline design and specification for the nucleonic, health and control instrumentation was therefore drawn up at Winfrith. The new requirements are mainly to provide ample flux coverage, to reduce spurious trips to a minimum, to follow the console layout of other Winfrith reactors and to employ nucleonic equipment in current use on the site. Most of the units are being provided by the Authority under a separate contract whilst the remaining equipment is being detail-designed and supplied by the reactor contractor.

The nucleonic coverage is briefly as follows:—

One switched linear power d.c. channel recording and indicating from 0 to 11 kW in 7 decades.

Two pulse channels indicating log power and doubling time and recording log power.

Two d.c. channels covering the range 10 mW to 50 kW indicating log power and recording log power and doubling time.

One d.c. channel indicating deviation from power.

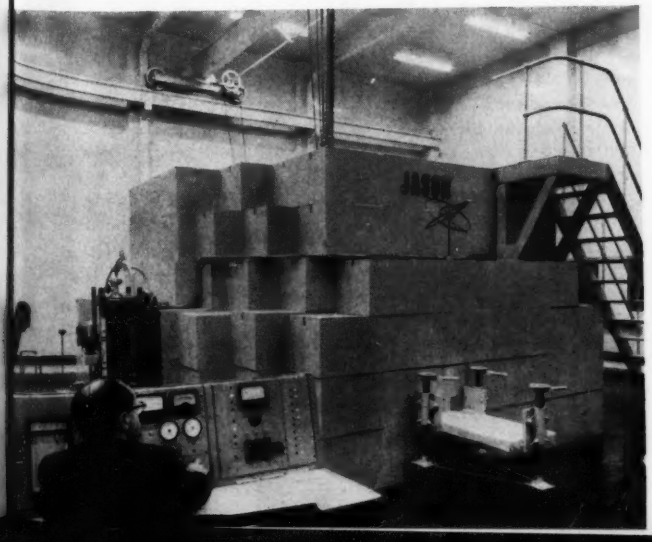
Three d.c. shut down channels provided with a two out of three coincidence trip system.

A conventional system of warnings and reactor trips is provided, both for start up and normal running conditions.

Five gamma health monitors are installed, one opposite each experimental cave and one above the reactor. These will provide warnings or reactor trips in the event of high gamma level being sensed.

The location of a total of nine neutron sensing devices presented a considerable problem. These are positioned in groups of three in vertical holes passing through four corners of the reactor top shield and into the graphite reflector, giving a total of twelve potential positions. At each corner one ⅛ in. diameter hole is for a pulse counting detector, and two 3½ in. diameter holes for ionisation chambers. Any of the detectors may be positioned between the core centre line and the top of the reflector, movement being controlled from above the top shield. To provide good neutron to gamma discrimination, 2 in. of lead is provided on the core side of positions and ½ in. behind.

The prototype Jason at Hawker's Langley laboratories. Based on the Argonaut design (see *Nuclear Engineering*, March 1960, p. 102) the reactor first went critical in September last year.



Shielding and Experimental Facilities

It was necessary in designing the reactor shield to bear in mind that each cave must be capable of accepting an experimental assembly of maximum dimensions 6 ft x 6 ft x 6 ft with additional height to permit the use of a transporting trolley. It must be possible to exchange assemblies with a minimum of effort, protection from shut down core gammas being given during this operation. A means of controlling the neutron leakage to any one of the four caves independently is required and there must be no interference between experiments. Experimental access for measurement is required over the whole of the outer face of each experiment and limited access above and at the sides.

The design of the cave walls, doors and roofs was influenced by the following considerations:—

(1) It must be possible to dismantle any part of the shielding with the minimum of disturbance in the vicinity, and to make use of a large proportion of the material in some new configuration.

(2) The general level of radiation is to be not more than 0.1 m.p.l. with the reactor at 10 kW power level. Leakage paths for fast neutrons must be reduced to a minimum owing to the proximity of other experiments using counting equipment.

The penetration of excessively thick walls is a considerable embarrassment when inserting fission chambers into assemblies or when inserting or withdrawing fuel rods containing foils. Thus, concrete made from chilled iron shot aggregate having a minimum density of 345 lb/ft^3 was selected, this being the most dense bulk shielding material available. Apart from the question of experimental access, it would have been impossible to produce a layout providing four adjacent caves if a shielding material having much greater bulk were used. It was obviously necessary to use precast block rather than mass concrete construction.

In order to reduce the direct gamma or neutron shine through joints between blocks, and at the same time preserve a simple rectangular form, it was decided to use a double wall construction with off-set joints. The majority of the blocks are of a standard size 1 ft 3 in. thick and 2 ft by 2 ft in elevation. To increase stability these are bolted in pairs giving a total wall thickness of 2 ft 6 in., such that the joints of the outer blocks are off-set from those of the inner by 2 in. In the construction of the walls, which are built dry, it may be necessary to use sheet steel packing between blocks to overcome manufacturing discrepancies. It has been necessary, of course, to provide a number of special blocks not conforming to the standard pattern. The blocks are framed in welded steel angles which not only provide corner protection but give support for the shuttering during placing of the concrete. The concrete density is checked both by weighing one in every 10 blocks and by test cube weighings. The density has in the main varied between 345 and 350 lb/ft^3.

The four cave roofs are supported entirely independently of the cave walls, on two linked portal frames fabricated from steel joists. Each roof consists of two layers 1 ft 6 in. thick made up of four slabs. There is through the roof a stepped removable plug giving vertical access of minimum size 18 in. square at the nominal centre line

of each experimental assembly. Recastable plugs, similar to those mentioned later in connection with the doors, will be provided. A series of removable blocks along each centre line extending from the 18 in. square hole for about 2 ft gives access in the shape of a cruciform to a minimum width of 6 in. It is thus possible to gain access for foil changing techniques and for fission chamber measurements across nearly the full length of the central lines of an assembly 6 ft square in plan, in addition to having universal access over the centre region.

The experimental assemblies, which can weigh up to 15 tons, are to be built on fabricated steel trollies which are supported on four roller skids which in turn rest on 1 in. thick steel plates mounted flush with the floor. The purpose of the steel decking is to spread the load without the complexity of using rails embedded in the floor. The movement of the trollies is guided by simple steel bars bolted to the plates. The rolling friction is of the order of 100 lb/ton. The 1 in. thick steel floor plates extend for some 20 ft from each cave mouth to permit re-stacking of the assemblies well away from the reactor. By a simple jacking arrangement it will be possible to lift the trollies and so turn the roller skids through 90° to permit side movement, and hence speed up the exchange of the assemblies.

The movement of the trollies, as in the case of the cave doors, is achieved by mobile electrically powered machines. A propelling force of 5,000 lb is produced by a hydraulic cylinder which is coupled at one end of the trolley or door, and at the other by a thrust pin which enters one of a series of holes in the steel floor decking. This device can push or pull, has a stroke of 3 ft and gives a moving speed under load of 4 ft per minute. For movements of greater than 3 ft a leap-frogging technique is required. Each unit is easily manœuvrable and the controls are at hand height.

To enable experimental assemblies to be inserted or withdrawn from the caves, doors are provided which can be rolled across the faces of the former. These are constructed of blocks in a similar manner to the cave walls, the assemblies being braced to welded steel trollies. As with the experimental trollies, the door trollies are mounted on four roller skids which also rest on 1 in. steel plates. The total weight of each door is of the order of 40 tons. To give experimental access through the doors, the standard blocks can be replaced by special blocks having stepped square holes, which, as in the case of the cave roof access holes, are filled with recastable plugs. These are in the form of steel liners, fitting the square holes closely, having removable plates bolted to inner and outer faces. To provide, for instance, holes for the insertion of fission chambers, tubes can be inserted in specific positions and the voidage inside the block filled with iron shot and paraffin wax. When an alternative configuration is required, the inner and outer cover plates can be scrapped, the iron shot and paraffin wax melted out and re-used in a reconstructed block employing the original liner. The outside of the liners and the access holes are stepped to prevent direct shine through the inevitable fitting gap.

It is necessary, when carrying out foil type experiments, to provide discrete irradiation times, and to this end a neutron shutter is provided. This consists of 4 in. of polythene with a cadmium layer, which provides a neutron attenuation of at least 10^3. As it is also necessary to gain access to the caves after reactor shut down, 8 in. of lead is provided to reduce the shut down core gamma activity to permissible levels. Both the neutron and gamma attenuators are combined to form four pairs of split balanced shutters which open and close vertically across each of the faces of the reflector. These shutters are motorized but can also be hand operated. The closing and opening time is approximately 0.5 min.

To complete the shielding between pairs of shutters at the four corners of the reflector, a combined neutron and gamma shielding material of lead shot and resin has been used. These four corner shield pillars, which are approximately 1 ft square in plan and 8 ft high, also provide a means of reducing interference between adjacent experimental assemblies, hence the necessity for the gamma and neutron shielding properties being multi directional. All the materials used in construction of the shutters and corner shield pillars have been chosen to keep induced activity to a minimum, for instance by the use of chemically pure lead and suitable aluminium alloys. Where steel members have been used in regions of flux high enough to cause activation (due mainly to the Fe^{59} decay gamma), cadmium sheet protected by aluminium has been applied. A similar method has been used on parts of the walls and roofs of the caves.

Initially the reactor top shield (which incorporates the rotating plug) will be backed up by two layers of iron shot concrete beams (core roof beams) of total thickness 3 ft resting on the inner edges of the cave roof slabs. These are easily removable to give access to the fuel element loading plugs, or control mechanisms after lifting the reactor top shield.

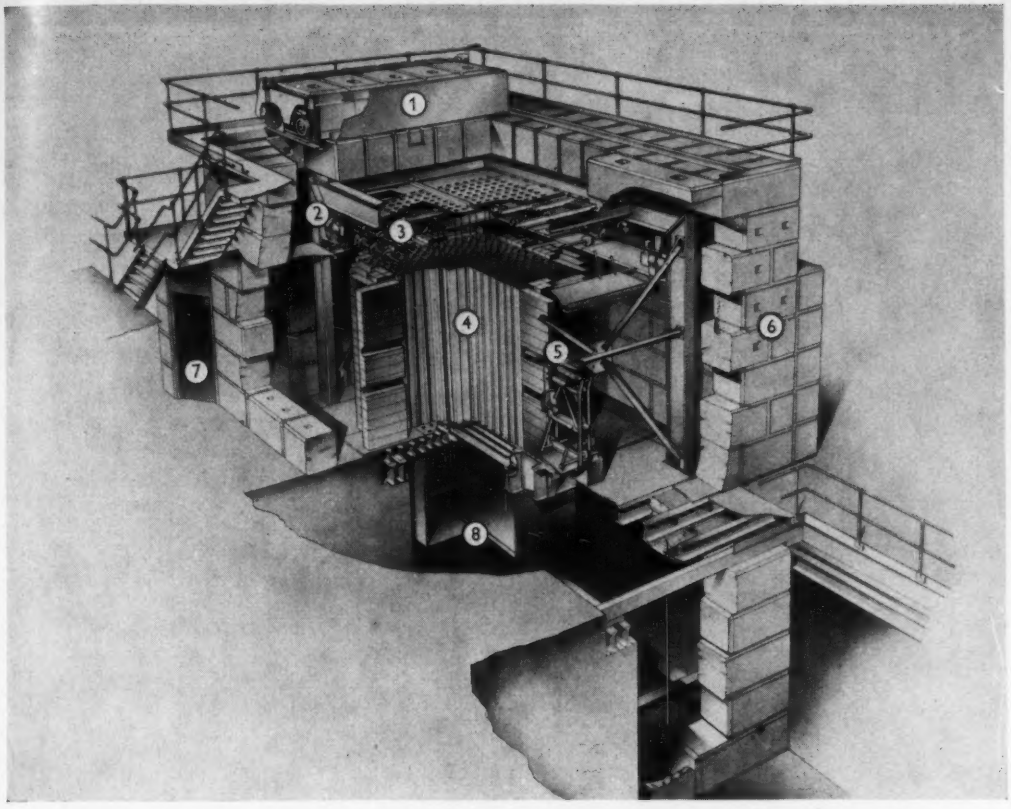
Vertical Beam Facilities

Eventually, the rotating plug will be replaced by one consisting of an aluminium shell filled with bismuth, to form a neutron window whilst still providing an adequate shut down gamma shield. The inner portal frames of the caves have been designed to withstand the load imposed by raising a wall above cave roof level to form a small top cave to take liquid moderated experiments up to 4 ft cube. There is also spare load carrying capacity to permit use of the existing core roof beams and complete the shielding above this cave. There will also be a secondary containment to safeguard the reactor from being flooded in the event of rupture of the tank of a liquid experiment. A liquid neutron shutter consisting of a tank containing water and boracic acid with a system of rapid filling and emptying, is under consideration to provide control of the neutron leakage to the experiment.

The problem of coupling between the reactor and experimental assemblies has been given considerable attention both by experiments on Hawker's Jason at Langley and by theoretical means. As changes in the degree of coupling can only occur when the shutters are operated, an overriding control of these is placed in the control room. Thus the reactor operator knows when any changes of reactivity are likely to occur, and can reverse the effect in the unlikely event of this being necessary.

It has been estimated that in the event of using small experimental assemblies, (say in the order of 3 ft cube), sufficient air activation would take place to provide an Argon-41 health hazard. Therefore, provision has been made to dilute the concentration by a ventilation system which gives an air change approximately every two minutes.

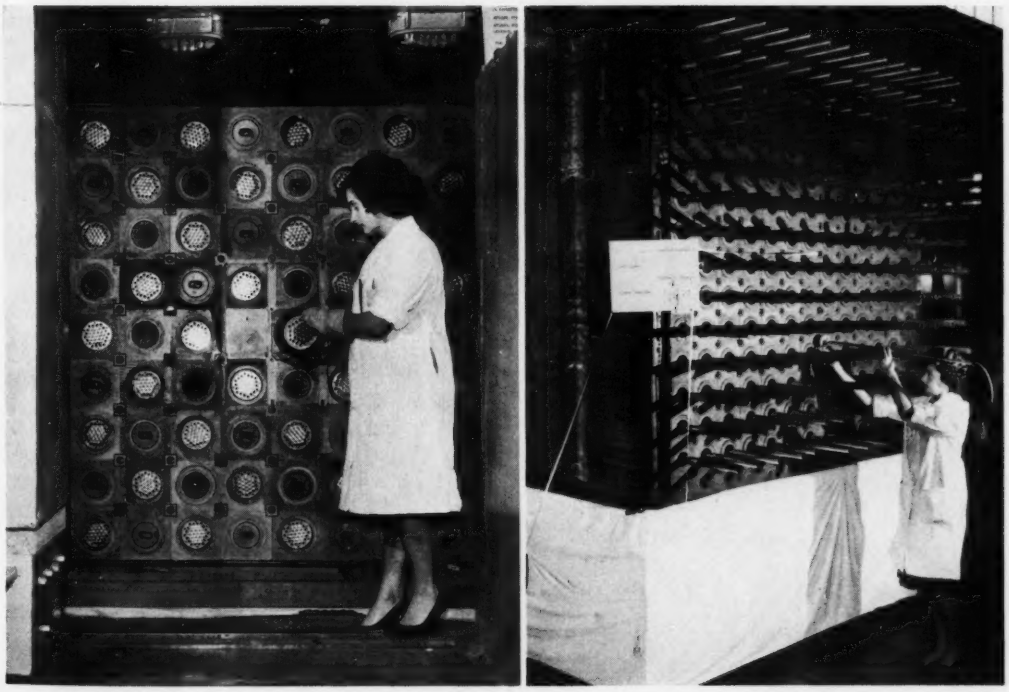
NESTOR, which will weigh some 500 tons, is being housed in the Reactor Physics Building at Winfrith in which there will also be a number of sub-critical experiments and several other reactors. The whole building is served by two 7.5 ton travelling cranes. The control room is at high level with a view over the area allocated to experimental work associated with the facility.



NERO

The zero energy reactor NERO as it was erected at Harwell and commissioned in 1957. It has now been dismantled and is being re-erected at Winfrith for operation in April, 1961. The reactor is suitable for determining critical sizes, the effectiveness of reflectors, the performance of control systems and for oscillator measurements. In this last respect it will be superseded by HECTOR, scheduled for completion in 1962. HECTOR is to be an advanced oscillator reactor with a fixed annular core driving a central heated experimental section, along the axis of which is located the hole for the oscillating rod.

KEY: 1. Removable top shield. 2. Control rod motors. 3. Control rod cables. 4. Experimental core. 5. Instrumentation channels. 6. Block shield. 7. Personnel access. 8. Sub-core room.



BICEP

The two BICEP stacks which are operated by the Consortia in collaboration with the AEA through the British Industrial Collaborative Exponential Programme. On the left is seen the fine structure stack and on the right the exponential experiment. AGR-type latticcs and fuels are currently under investigation.

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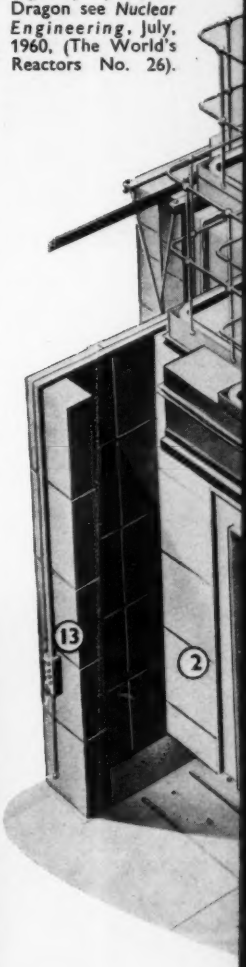
For details of the zero e reactor ZENITH built to stud physics of the HTGC reacto *Nuclear Engineering*, Nov., (The World's Reactors No. For details of the OEEC Eur Nuclear Energy Agency's project Dragon see *Nuclear Engineering*, July, 1960, (The World's Reactors No. 26).



1. Cave structure. and access system shutters. 6. Corr shutter mechanism 9. Shield doors. 11. Door/stack mo stack. 13. Neutro 15. Reflector. 1 Control rods. 19. N_a sparge. 2 inner vessel. 22. 24. Top shield. 25 27. Steel floor.

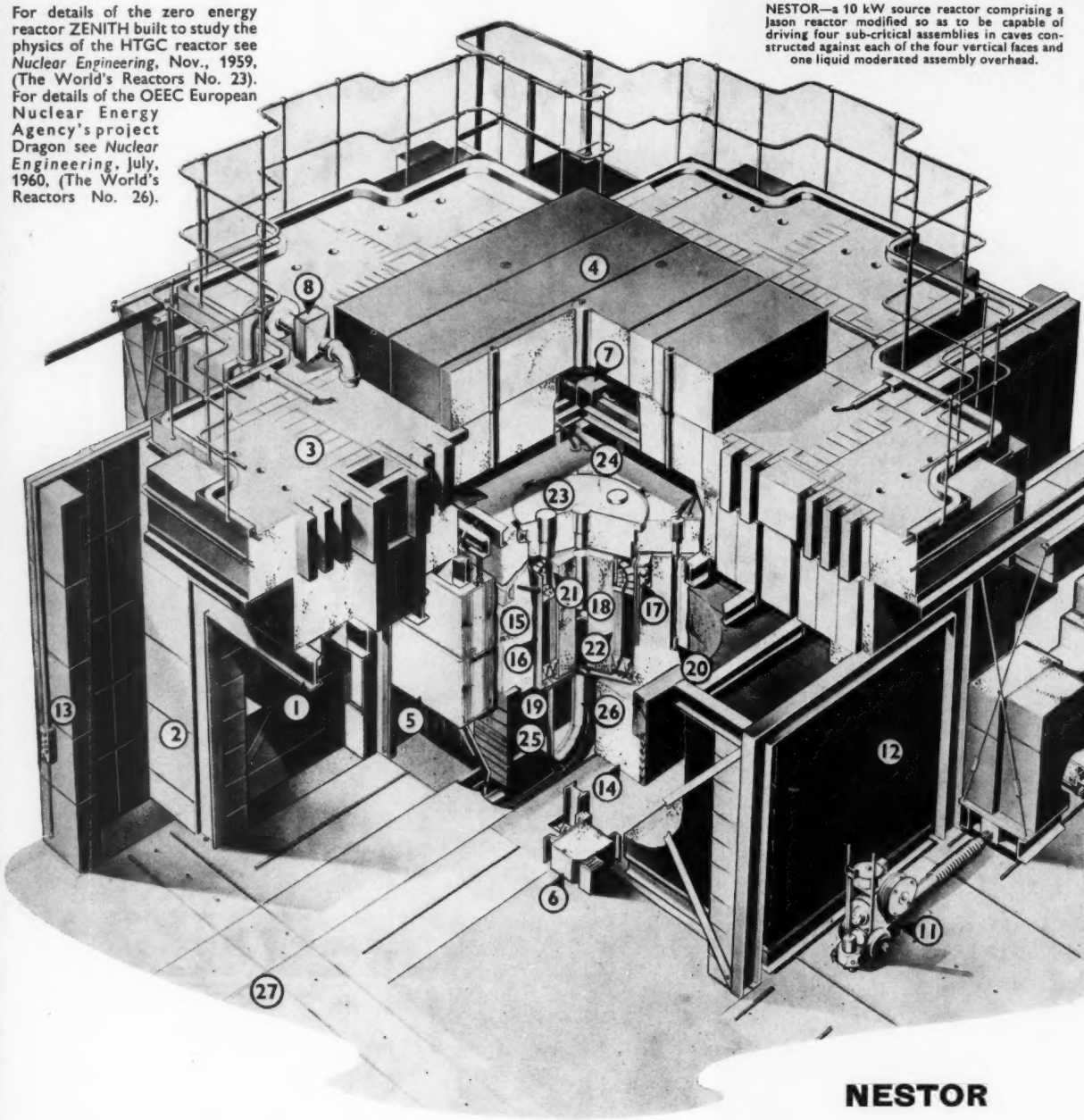
Nuclear Engineering

REF. SHEET NO. 3: GRAPHITE ASSEMBLIES*

*for the Magnox and AGR programmes at the U.K. AEA's establishment, AEE, Winfrith.

For details of the zero energy reactor ZENITH built to study the physics of the HTGC reactor see *Nuclear Engineering*, Nov., 1959, (The World's Reactors No. 23). For details of the OEEC European Nuclear Energy Agency's project Dragon see *Nuclear Engineering*, July, 1960, (The World's Reactors No. 26).

NESTOR—a 10 kW source reactor comprising a Jason reactor modified so as to be capable of driving four sub-critical assemblies in caves constructed against each of the four vertical faces and one liquid moderated assembly overhead.



NESTOR

NESTOR

1. Cave structure. 2. Cave wall. 3. Cave roof and access system. 4. Core roof. 5. Neutron shutters. 6. Corner shield pillar. 7. Neutron shutter mechanism. 8. Ventilation fan and filter. 9. Shield doors. 10. Recastable access plug. 11. Door/stack moving mechanism. 12. Graphite stack. 13. Neutron shutter controls. 14. Plinth. 15. Reflector. 16. Reactor outer vessel. 17. Control rods. 18. Central thermal column. 19. N_2 sparge. 20. Ion chamber. 21. Reactor inner vessel. 22. Fuel box. 23. Rotating plug. 24. Top shield. 25. Lead shield. 26. Dump pipe. 27. Steel floor.

SCORPIO 1

1. Heat exchanger. 2. Exhaust chimney. 3. Stack cooling blower. 4. Stairway. 5. Control console. 6. Nitrogen reservoir. 7. Alpha monitors. 8. Differential pressure blower. 9. Pre-heat oven. 10. Access platform. 11. Personnel chamber. 12. Personnel door. 13. Source flask. 14. Alpha containment. 15. Emergency ladder. 16. Graphite plinth. 17. Alpha monitor gas cooler. 18. Main switchboard. 19. Micafil insulation. 20. Graphite stack. 21. Personnel chamber blower. 22. Slide mechanism. 23. Main and circular doors. 24. Insulating floor. 25. Sindanyo insulation. 26. Electric heater mats. 27. Insulation.

SCORPIO 2

1. Differential pressure blower. 2. Containment shut off valves. 3. Relief valves. 4. Heat exchanger. 5. Cooling chamber valve controls. 6. Nitrogen reservoir. 7. Personnel door. 8. Shielding door. 9. Biological shielding. 10. Alpha monitor. 11. Control console. 12. Contactor panel. 13. Emergency lighting unit. 14. Stack chamber door. 15. Transfer trolley. 16. Working table. 17. Main switchboard. 18. Alpha containment. 19. Stack chamber. 20. Emergency exit. 21. Alpha monitor gas cooler. 22. Personnel-chamber blower. 23. Graphite stack. 24. Cooling chamber. 25. Pre-heat oven. 26. Personnel chamber.

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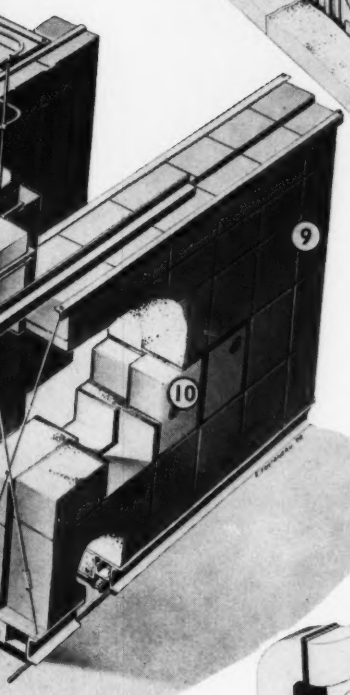
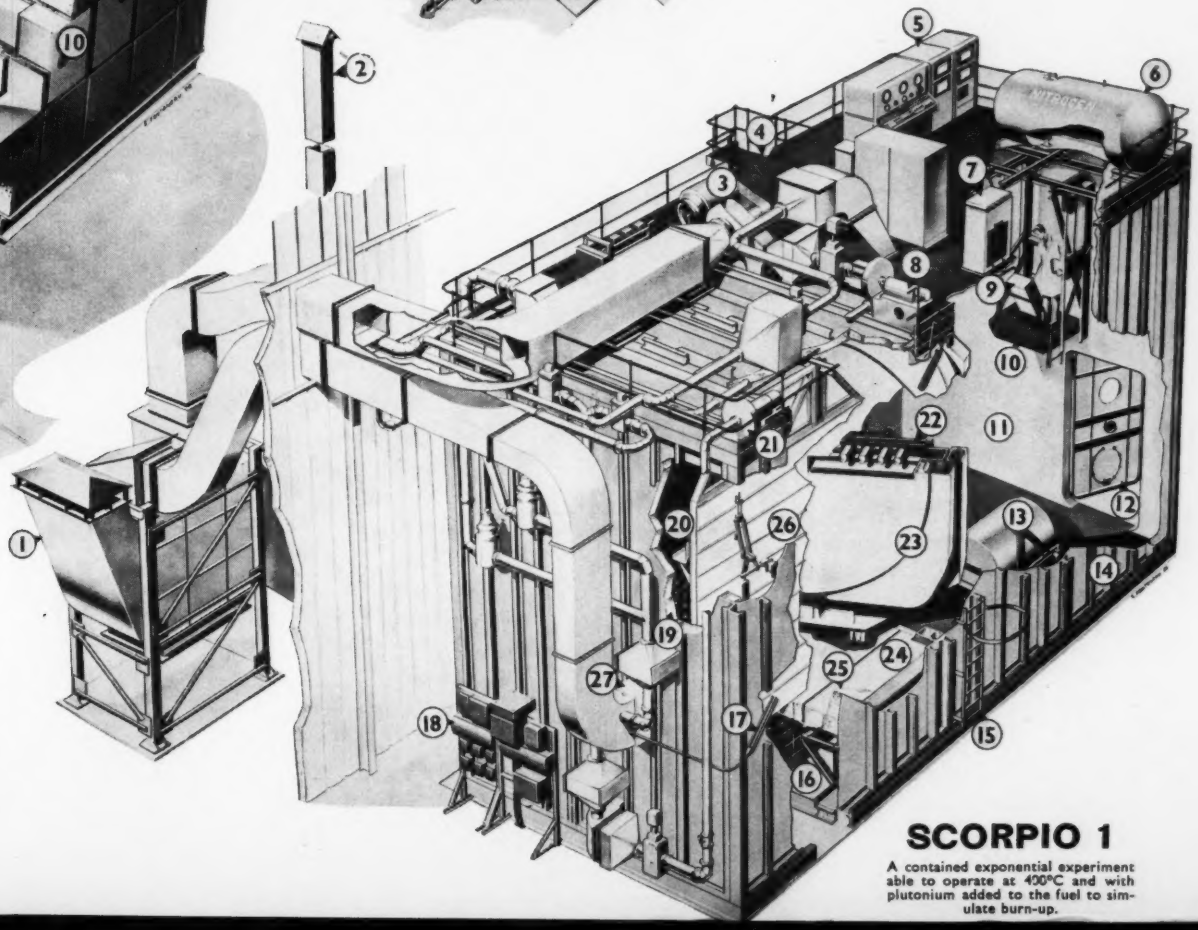


SCORPIO 2

A contained fine structure stack for determining the effects of burn-up at temperatures up to 400°C.



SCORPIO 1

A contained exponential experiment able to operate at 400°C and with plutonium added to the fuel to simulate burn-up.

ainment
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Transfer
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9. Stack
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AEE, Winfrith

IN a remarkably short space of time the facilities at the AEA's Atomic Energy Establishment at Winfrith have taken shape and the site is already well on the way to becoming the finest reactor physics research institution in the world. Permission to develop 1,100 acres of open heathland in Dorset was granted in February, 1957, and work on the site was begun on September 2, 1957. Staff at present totals approximately 2,000. After the provision of access roads and basic site buildings, one of the first tasks was to install the effluent treatment plant, the disposal system terminating in a 2-mile pipe line into the English Channel.

The first major research installation on the site was the zero energy reactor ZENITH (*Nuclear Engineering*, Nov. 1959, p. 386), which is currently being used to provide the basic reactor physics information for the Dragon project and will, in future, be used by the Authority for studies going beyond this immediate objective. The design of the Dragon experiment itself, and the organization handling it was described in *Nuclear Engineering*, July, 1960.

The Dragon project is staffed by nationals of twelve European countries, including staff from the U.K. AEA, and it is managed by a Chief Executive who is responsible to a Board of Management composed of representatives of the signatories of the Dragon Agreement. This Agreement was signed early in 1959 and is to run for five years; at the end of the Agreement the U.K. assets of the project, notably the reactor experiment, pass into the possession of the U.K. AEA. During the period of the Agreement the Authority is providing the project with engineering and administrative services. A sharp distinction should, however, be drawn between the work of the Dragon project and the Authority's work being carried out at the establishment, which is concerned with the U.K.'s national programme for the development and exploitation of nuclear energy.

Winfrith has become one of the main centres for reactor physics research in the United Kingdom and, initially at least, attention continues to be focused on the graphite moderated reactors with particular emphasis on the Magnox stations, the AGR, and the Authority's independent interest (i.e., outside Dragon) in high temperature gas cooled systems. Research is not entirely confined to graphite moderation and exploratory work is under way on water moderated and organic moderated systems. Electronics and engineering research groups have also been established to undertake basic investigations and development relating to control systems and heat transfer and transport in reactors. The work carried out at Winfrith has been transferred from Harwell over the past two years; some of the equipment needed was also transferred although new experimental tools have been provided where necessary.

Reactor Physics

The principal items of plant around which the low and medium temperature graphite research are conducted are illustrated in the accompanying pull-out. Chronologically the first stacks to be transferred to Winfrith were those set up under BICEP (British Industries Collaborative Exponential Programme), the two units comprising an exponential stack and a fine structure stack, both of which were designed to measure basic physics parameters over a wide range of

Work on the foundations for the Dragon experiment is proceeding: the main civil engineering contractor is Turriff Construction Corporation.

lattice dimensions and with a variety of fuel elements (see *Nuclear Engineering*, April, 1960, p. 149). Whilst the initial work concentrated upon developing theories to correlate with experimental results obtained on Magnox lattices attention has recently been diverted to structures of the AGR type with fuel element bundles rather than single rods.

Work is confined to ambient temperatures, so for high temperature studies two somewhat similar units have been built which can operate up to 400°C. These are called SCORPIO I and II, SCORPIO II being for the fine structure measurements.

In SCORPIO I the graphite stack is variable in frontal area from 5 ft square to 12 ft square, the depth along the fuel rods being 7 ft or 9 ft 4 in. It is heated by a number of radiant electrical heaters with a total consumption of 288 kW and is contained in a thermally insulated chamber. Pressure differentials are maintained to ensure that leakage can only occur away from the personnel chamber into the stack chamber.

A large door separates the two compartments and provides access for erection of new lattice configurations. This door is fitted with a rotating circular panel with an access slide, which enables flux measuring devices to be inserted at any point in the stack.

Neutron sources are provided and, during experiments, are located in the thermally insulated graphite plinth beneath the stack. The heating cycle is automatically controlled and recorded and takes a maximum of 48 hours. Continuous-running alpha-monitors are incorporated and all ducts to atmosphere are guarded with glass paper filters and fitted with automatic shut-off valves. Fire precautions

Disposal of radioactive effluent has been given careful attention at Winfrith. This picture shows lengths of piping preparatory to installation off the Dorset coast.

installations are built-in to handle any possible outbreak in either chamber.

The fine structure experiment comprises machined blocks forming a rectangular stack of maximum dimensions 6 ft x 6 ft x 4 ft 8 in., the last dimension being the length in the direction of the fuel channels. The stack is heated by radiation from electric heaters situated on the top and bottom faces. It is cooled by the closed circuit gas system entering and leaving the stack chamber on the same faces as the heaters. The stack is enclosed in a primary containment and access to a central block of graphite is obtained through a sealed door.

A large-area antimony-beryllium source is provided to give the necessary uniform flux of thermal neutrons. The beryllium tubes are housed in a fixed plinth on one face of the stack, radioactive antimony being inserted when radiation is required. Owing to the intense gamma radiation produced, the antimony is held in a source flask while operators are working on the stack and is inserted mechanically from an external control console.

One of the major tasks of these two constructions is to determine the effects of burn-up. At present work is still concerned with natural uranium only, but burn-up is to be simulated by replacing the natural uranium with depleted uranium rods having attached to the outside flat plates of plutonium aluminium alloy canned in aluminium. Later, plates of plutonium uranium alloy will be used. Because of this use of plutonium it is necessary to contain the units in steel shells to prevent any possibility of outside contamination.

Control desk and panel for ZENITH.

With particular reference to the use of sleeves and Be canning in the AGR project, changes in neutron flux and spectrum with temperature are being studied in a differentially heated graphite assembly capable of operating between ambient temperatures and 400°C. In the present assembly a graphite stack has been built up with six channels regularly disposed around a thermally insulated central channel. The outer channels are provided with graphite liners and large beryllium tubes simulating tube clusters while the central channel is fitted with a graphite liner and a 37-tube beryllium cluster. Heating is achieved by electrical resistance heating of the liners and tubes. Antimony-beryllium sources mounted in the supporting graphite plinth energize the stack and spectrum changes at different temperature differentials are determined by shifts in the uranium plutonium fission ratio as measured in small fission chambers. Because of the toxicity problem associated with beryllium experiments, a degree of containment and careful control of the ventilation systems are necessary.

Special fuel element section for neutron fine structure measurements on BICEP 2.

For investigating reactor physics problems on critical assemblies, the versatile zero energy reactor NERO is being moved from Harwell and is scheduled to come into operation early in April. Basically this reactor comprises a 14 ft cube the lattice pitch of which can be varied at will as also can the fuel elements and control rod positioning. The reactor can also be used for oscillator experiments but in this context will be superseded by HECTOR, construction of which has now been started with operation scheduled for 1962. This reactor will comprise essentially an annular critical core, surrounding a central experimental region into which different stacks can be assembled and brought up to temperature leaving a central hole for an oscillating rod. The final designs, which are just being completed, contain many novel approaches to research reactor problems and great store is set by the versatility and usefulness of this particular device.

To complete the series of graphite machines will be the subcritical facilities to be built in the irradiation caves round the source reactor NESTOR. The design and functions of this particular facility are discussed in the

preceding and following articles. The facility is also capable of being used with water-moderated assemblies or indeed any configuration of modest size.

Liquid and Fast Systems

Experiments have already begun on the liquid moderated subcritical assembly HELEN. This system, designed to use organic materials when necessary, is at present working with plutonium fuels with light water moderation. The fuel is in the form of plutonium aluminium alloy strips which are suspended in an aluminium tank of water. Because of the toxicity problem an extensive system of shielding and containment is necessary with provision for measuring flux automatically by remotely controlled fission chambers and a special system for remote handling of the fuel.

A zero energy reactor for providing physics data for the fast reactor programme is also being constructed at Winfrith—ZEBRA—and is due for commissioning in 1962. The reactor is designed to continue the basic research that has been conducted at Harwell on ZEPHYR and ZEUS.

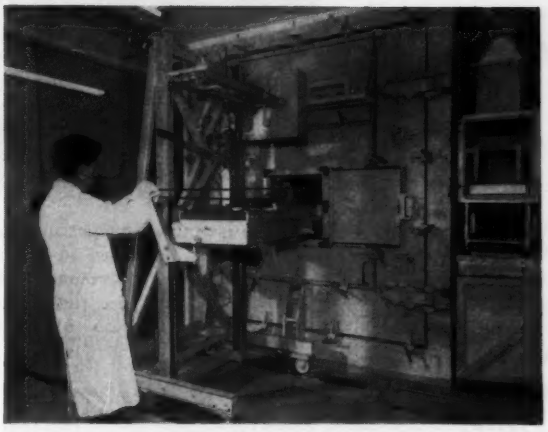
DIMPLE, the heavy water zero energy reactor at Harwell is to be taken down and re-erected at Winfrith for experimental work on heavy water moderated systems, such as the SGHWR.

Engineering Research

Certain engineering research projects have been initiated at Winfrith or moved down from Harwell, as for example, the gas bearing development work which has particular significance in the high temperature gas cooled programme.

In the fuel element laboratory, out-of-pile testing of the behaviour of thin walled cans under varying loads and at varying temperatures is under way and the modes of failure found in practice compared with theoretical predictions and correlations attempted. The effects of stiffeners, the result of strain cycling, creep and fatigue are amongst the features at present under examination.

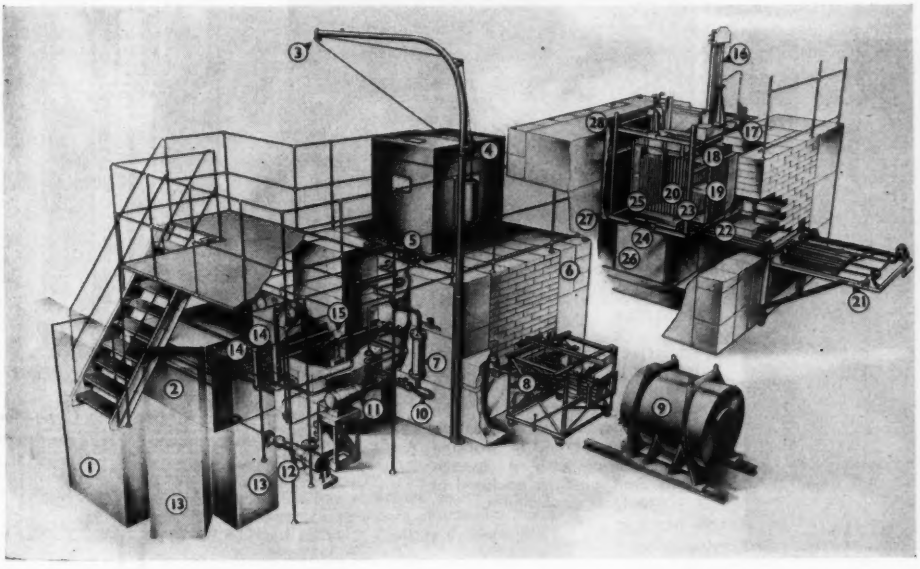
Experience is being gained in the handling of hot organic materials and, in addition to heat transfer work and radiolytic breakdown measurements, development work has been undertaken on suitable pumps. On the heat transfer rigs investigations have shown that the heat transfer properties of Santowax R can be predicted from the physical properties and from the conditions of operation by accepted correlations for forced convection. Maximum temperature in these rigs has been 400°C with heat transfer rates of up to 350 W/cm². Work is now beginning on repeating these measurements for varying concentrations of high boiler fraction.



Transferring a graphite block from SCORPIO II stack by special trolley to the cooling chamber.

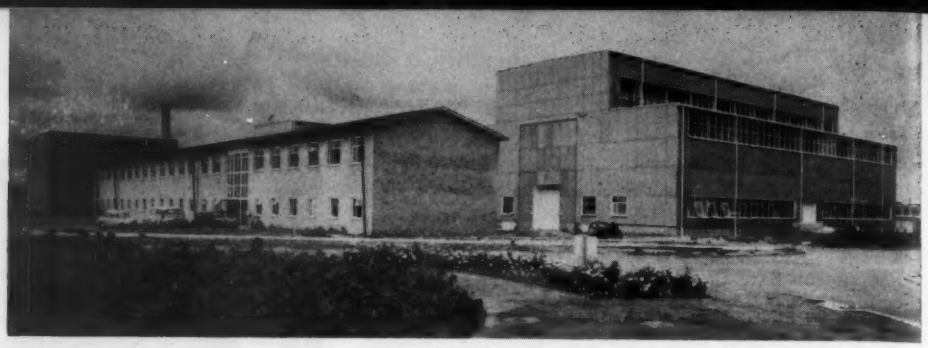
Long trouble-free operation has been obtained with submersible pumps operating with a hot Santowax R circuit with the organic in contact with the windings. The windings are insulated from each other by ceramic beads but the leads, stator and rotor windings are in contact with the fluid. Although a run of 1,000 hours at 420°C has been achieved it is felt that probably 350°C is the limit for this immersed winding technique. A variant suitable for higher temperatures which has to date worked successfully for six months continuously at 300°C uses a stator canned in 0.02 in. stainless steel with the windings contained in an inert gas atmosphere. Insulation between leads is provided by ceramic beads as before.

A programme of boiling water heat transfer work and the study of the various regimes of boiling have been



HELEN

1.—Control panels
2.—Dump tank
3.—Jib for concentrator
4.—Concentrator
5.—Connections to plutonium monitor
6.—Concrete shielding
7.—Ion exchange column
8.—Flexible source loading tubes
9.—Transport flask
10.—Ion exchange pump
11.—Draining pump
12.—Filling pump
13.—Plutonium monitor
14.—Filters
15.—Dump valve
16.—Scanner
17.—Vertical scan support beam
18.—Fuel security locking bar
19.—Fuel beam
20.—Fuel plates
21.—Source positioning unit
22.—Core support frame
23.—Beryllia blocks
24.—Antimony bars
25.—Beryllium cylinders
26.—Graphite reflector
27.—Core tank
28.—Corrosion specimen carrier



A typical Winfrith building—one of the Zero Energy Halls with its associated laboratory block in front.

instituted and bubble formation is studied by passing air under pressure through porous pipes immersed in water tanks. The bulk of the work, however, at present is at ambient pressure which while simplifying the rigs complicates the measurement. The construction of high pressure assemblies at a later date can be presumed.

Instrumentation

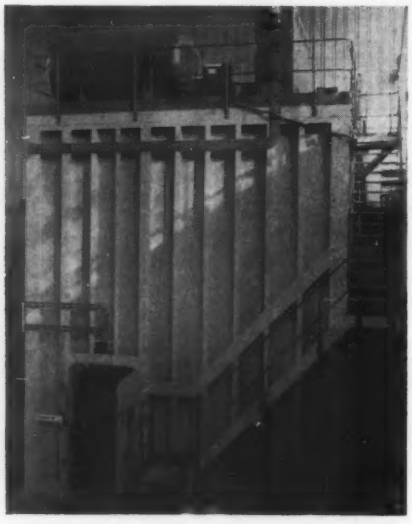
In the instrumentation group responsibilities are two-fold. The establishment itself provides a great deal of work for a number of people in its requirements for specialized instrumentation, but Winfrith can now be considered a major centre for the development of new control systems for reactors in this country. Apart from such items as the construction of transistorized power supplies considerable effort is being put into the development of a transistor scanning technique. A conventional interlock circuit requiring a multiplicity of relays with many contacts could be replaced by a system which looks at each instrument in turn and then determines the status of each of these at the end of the cycle. The rapidity of scanning can be so fast that the implied dead time is negligible and systems such as six out of eight can be built up from quite simple components and without the use of slave circuits. An alternative to the use of relays in circuits of up to a two-out-of-three logic involves the use of ferrite cores with an almost rectangular hysteresis curve and an almost flat saturation characteristic. One winding of the core includes the instrument contact and a rectifying circuit, a second carries the interrogation pulse of 10 μ sec width and a third circuit conveys the output signal. The windings are so arranged that if the instrument relay is closed the interrogation pulse charges the d.c. circuit and also transmits on through the signal circuit which can be used as an interrogation pulse for the next system. If the instrument relay is broken then the coil saturates and no onward transmission results. The final output can be amplified by magnetic amplifiers to actuate the controlled unit. This system is still in the experimental stage but it would appear to provide a continuous scanning of the interlock circuits themselves in which no "sticking" is possible. Annunciation is also simplified in that the d.c. circuit associated with each coil can include a visual indicator.

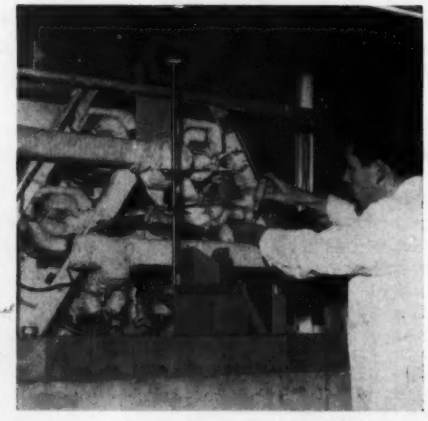
The work of the establishment is backed by comprehensive computing facilities, the equipment including a Mercury digital computer with a storage of 32,000 numbers and a Pace general purpose analogue computer which is capable of high accuracies. The plug-board system of setting up enables complex analogue systems to be set up quickly, coefficients being established on pre-punched paper tape.

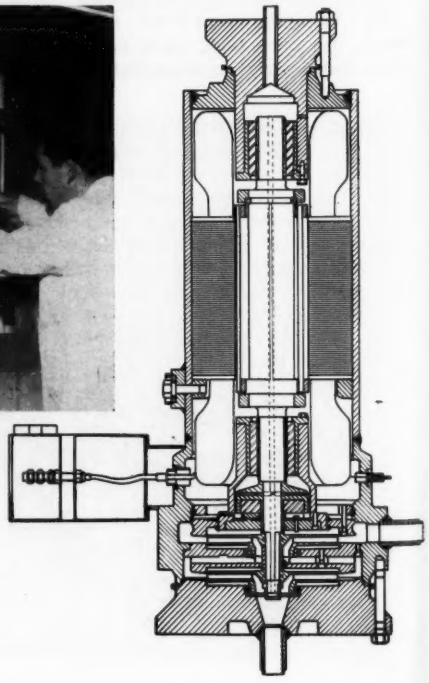
With such a rapid build up of the establishment, in some instances the initiation of a programme has been ahead of the building programme. As a result the gas bearing department is housed in with health physics and at some later stage it will be necessary to move SCORPIO I and II in order to house the engineering research under one roof. The general approach has, however, been to provide hangar-like structures of cheap construction in which equipment can be fitted rather than to think in terms of special-purpose elaborate constructions.

Right.—The differentially heated stack built by Vickers Nuclear Engineering.

Below.—The steel containment shell of SCORPIO I.







Immersed winding pump manufactured by Hayward-Tyler suitable for organic liquids at temperatures up to 350°C. The company has evolved a variant on this design for higher working temperatures with a canned stator and windings enclosed in an inert atmosphere.

Integral Experiments for Power Reactor Design

Types of Experiments to be carried out in NESTOR

by G. W. K. FORD, M.A. (Cantab.)
(*AEE, Winfrith*)

METHODS of estimating the important nuclear characteristics, such as critical size, temperature coefficients and effects of control rods and burn-up, for power reactor design purposes vary considerably, depending upon the type of reactor. In the present state of reactor development, in all cases, a combination of both theoretical analysis and semi-direct experimental investigation is found necessary. In principle, if all the fundamental nuclear data such as scattering, absorption and fission cross-sections and neutron yields were accurately known from basic measurements for all the materials of construction and for all the product nuclei from the nuclear reactions which will take place during the life of the reactor, then the application of a sufficiently comprehensive reactor theory would enable an adequate prediction of a reactor's initial and long-term performance to be made.

Nevertheless, although progress is continuously being made towards this goal, present methods of reactor design rely heavily upon integral experiments in which are measured the overall nuclear reaction rates, neutron distributions and characteristic dimensions which result from exposing the actual reactor nuclei in their correct geometrical inter-relationship to a self-conditioning neutron environment. Such experiments, if properly designed, automatically produce the correct reactor spectrum (including, approximately, temperature effects if the assembly is artificially heated) together with the right degrees of self-shielding, flux-depression and so on, and enable the type of nuclear information required for reactor design to be obtained in a rather direct manner. These experimental results can be analysed and used to obtain design constants with a minimum of reference to basic nuclear data in those cases where the simplest methods for semi-empirical correlation of experimental results are employed; but for more advanced methods of analysis the fundamental data must be extensively incorporated. The former approach, using two groups of neutron energy in a simple diffusion theory, has yielded the types of calculational methods adopted by the U.K. AEA[1,2] and the Consortia for the design of the Magnox and the AGR types of graphite moderated reactor. Similar methods of semi-empirical analysis of reactor lattice data are also used for water-moderated reactors, both using two-group theory[2] and greater numbers of neutron energy groups[3].

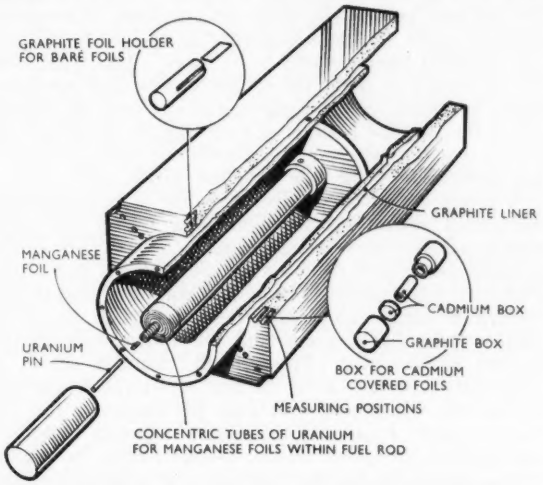


Fig. 1.—Typical arrangement of fine structure experiment in a graphite lattice. Note concentric cylinders of uranium metal to enable foils to be inserted in fuel. *Courtesy C. Hunt, AEE, Winfrith (Ref. 4).*

The reactor lattice experiments used for these purposes fall into two main categories, critical and sub-critical. Approach-to-critical experiments, which in effect come between these two main classes, have rather limited utility (largely on account of their inherently low flux levels), giving in the main only approximate values of critical size and little else, whilst requiring almost as many safety precautions as critical systems. In critical systems the nuclear reaction is self-sustaining and no external supply of neutrons is required, whilst the neutron flux may be set at any convenient intensity within the assembly by adjusting the control rods. It is necessary to feed neutrons from an external supply into a sub-critical experiment in order to excite a neutron population within the lattice, and the intensity attained depends directly upon the power of the neutron source. All the data required for design purposes could, in fact, be obtained from critical systems alone, but for many types of reactor it is more economical in materials and experimental effort to use a combination of both types of experiment. In others, of which the fast reactor is a notable example, satisfactory techniques for sub-critical experimentation have not yet been devised and all the required data has to be obtained from critical experiments, even though the investment of fissile material in a fast assembly may prove to be extremely costly for a power reactor system. In these circumstances it is clearly a difficult and expensive matter to change from experimentation upon one fissile material to another, or even to change the geometry or density of a given fuel. In such cases the best that can at present be done to economize in special fuel investment and fabrication effort is to use a two-region technique in a system which is critical overall and in which the centrally situated test region is sufficiently large to ensure the development within its inner volume of a neutron spectrum adequately in equilibrium with its environment and representative of the sample.

In the case of thermal neutron reactors a combination of critical and sub-critical experiments can be used, especially for reactor systems which are physically large, so that the sub-critical "samples" are big enough to ensure that a large region of equilibrium spectrum is available to provide an adequate measuring region. In more compact thermal systems, on the other hand, the critical experiment becomes relatively more important and, fortunately, also

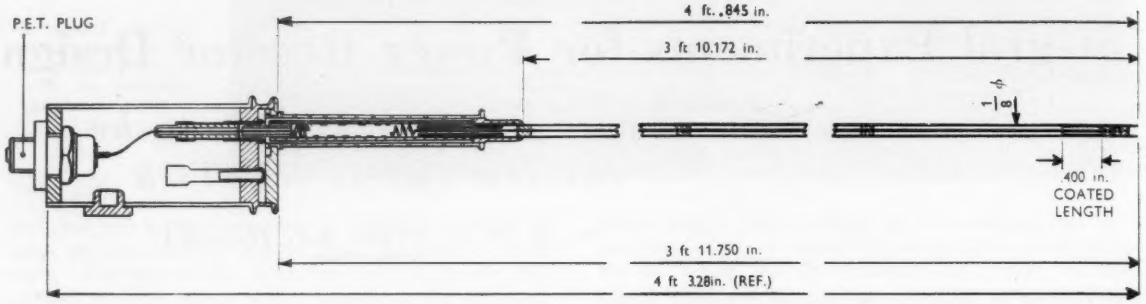


Fig. 2.—Construction of miniature cylindrical fission chamber for intensive parameter measurement. Extension tube could be many feet longer. *Courtesy W. R. Loosemore, AERE, Harwell (From ref. 5).*

cheaper, both in equipment and fuel costs. Furthermore, two-region or multi-region methods are being increasingly developed for use in both critical and sub-critical experiments upon some systems in order further to economize both in materials fabrication and inventory costs, and in experimental effort. Sub-critical experiments are economical in equipment and experimental effort because, besides requiring a much smaller reactor materials inventory they have no need of control and shut-off devices.

For the study of the cores of low enrichment reactors of large power output, in which case the core size may be very great, the sub-critical method becomes most desirable for reasons of economy, and fortunately in such systems adequate design data may often be obtained entirely from the analysis of results obtained from sub-critical experiments. Such sub-critical data can, however, be usefully extended by small enriched-fuel critical assemblies and further supplemented by critical data from the assembly and operation of power reactors.

Parallel Investigations

In the experimental investigation of these large reactor cores the use of several relatively cheap sub-critical experiments in the investigation of a reactor system allows a greater range of more detailed experiments to be carried out in parallel than can be achieved if only one critical assembly is available for the reactor design programme. Small critical experiments are a desirable supplement to the sub-critical experiments for some important measurements, including investigations upon non-uniformly distributed or partially inserted control rods, kinetic experiments and tests in which the accurate observation of small effects upon reactivity are required. Examples are the influence of small changes in temperature at a given temperature level, and the perturbation produced by small quantities of fissile or absorbing material placed in various regions of the reactor (including, for example, the measurement of adjoint flux distribution). All the other important measurements, however, including in particular those of buckling and fine structure, can be carried out with an entirely adequate accuracy using sub-critical systems. These measurements again fall essentially into two main categories. First are those concerned with extensive parameters, that is the measurement of the average variations of neutron population over the reactor as a whole (of which the buckling, or curvature of the neutron population distribution in the unperturbed, uniform reactor lattice is the most important). Second are those dealing with the intensive parameters, comprising on the one hand the detailed variations of the low-energy neutron flux within one lattice cell in both space (the fine structure of neutron flux distribution) and energy (the neutron energy spectrum), and on the other the detailed nuclear processes taking place within the fuel itself. These include the fast fission factor (e.g., fission rate of U^{238} nuclei by fast neutrons compared with fission rate of U^{235} nuclei by slow neutrons) and the conversion factor (e.g., transmutation rate of U^{238} into Pu^{239} by neutron capture compared with rate of destruction of U^{235} nuclei).

The extensive parameters, of which the most important is the buckling, are measured in an exponential experiment, which consists of a representative sample volume of the reactor lattice being investigated (all lattice components being of full size) which is considerably smaller than the critical volume but sufficiently large to ensure that boundary effects do not perturb the macroscopic neutron distribution which has to be measured. For experiments on solid moderator systems the sample is usually approximately cubic in shape and neutrons must be fed in to one side of the sample from a suitable neutron source. In order to obtain the required type of measurement the neutron population must fall exponentially with distance away from the source plane, a requirement which is satisfactorily met provided the sides of the exponential assembly are no longer than those of a similar cubic assembly which, if built out along one axis to an infinite distance, would just become critical. However, in a heterogeneous system the assembly must also be large enough to ensure that there are sufficient lattice cells along the directions of measurement to enable an adequate number of neutron population (or intensity) measurements to be made. This is because it is necessary to make the extensive parameter measurements at similar or corresponding points over the lattice, i.e., at the identical position in each adjacent lattice cell, to ensure that the extensive flux distribution measurement is not perturbed by the fine structure within each cell.

A typical exponential experiment for a light-hydrogen moderated power reactor might be a 3-ft or 4-ft cube lattice sample, and would require a fairly powerful neutron source to feed it. As it could have a free liquid surface it is convenient to be able to insert fuel rods (either vertical or horizontal) through this free surface and to be able to feed the neutrons into the system through the bottom of the tank. Provided the neutron source is sufficiently powerful, as in the case of NESTOR, such an exponential experiment can also be employed for the measurement of intensive parameters, although if desired an additional somewhat smaller assembly could be utilized to save radioactivating the relatively large quantities of fuel invested in an exponential experiment in the higher fluxes required for these measurements. The use of one or more auxiliary experiments for the intensive parameters also

allows a more detailed exploration of complex lattice cell geometries to be made than could reasonably be achieved in the exponential.

With graphite (and heavy water) low-enrichment lattices it is even more desirable to sub-divide the functions of the different types of experiment on account of the much larger sizes of the lattice samples necessary. An exponential experiment upon a natural-uranium, graphite-moderated system, for example, will employ an unreflected sample of the lattice of the reactor being studied in the form of a cube some 10 ft on the side, compared with some 30 to 50 ft for the full-scale reactor: note that this sample, although apparently large, is nevertheless less than a tenth or a twentieth of the effective volume (and cost) of a full-size core. A sufficiently intense neutron population (around 10^4 n/cm² sec) may be excited within such an experiment by means of a few one-curie radium (alpha) beryllium sources (usually four) placed in a thermalizing source-slab of reactor graphite of similar cross-sectional area to the experimental cube and placed in contact with the lattice cube. This low intensity suffices because as the measurement positions extend over a large linear distance (i.e. 10 ft or so) the detecting device may average a fairly large volume of the local fine structure flux, and detecting foils or counter tubes can be relatively large in size. One may employ, for example, a BF_3 counter ½ in. or 1 in. diameter by a few inches in length or metal foils of about 1 in.² in area containing perhaps 0.3g of indium or manganese. In addition, the neutron population to be measured is well thermalized and the detecting devices therefore have an inherently large sensitivity; also the lattice-points chosen for measurement may be at points of maximum thermal neutron flux, i.e. mid-way between fuel elements.

Intensive Parameter Measurements

The fine structure of thermal neutron population (or flux), on the other hand, requires measurements to be made over the distance of a half lattice pitch only, that is some 3½ to 8 in. only in a low-enrichment graphite reactor, and must extend from the high flux inter-cell position to the centre of the fuel which is the position of minimum thermal neutron flux (see Fig. 1). The finer spatial resolution required calls for physically smaller detecting instruments which therefore contain less detecting material and are thus less sensitive. Typically the metal foils employed are only some one-tenth or even a hundredth of the area and mass of the foils which may be used in a graphite exponential experiment. This lower detector sensitivity, together with the need to measure in regions of flux depression, gives rise to the need for a tenfold or one hundredfold larger neutron flux intensity in the region of measurement than is necessary in an exponential experiment.

It is only necessary to assemble for the experiment a sufficient total volume of the reactor lattice to ensure that the neutron energy spectrum in the relatively small test region is properly representative of the reactor as a whole, i.e. that the flux in the test cell is in spectral equilibrium. This is found to require only three or four lattice pitches all round the test cell, giving rise to the need for only a comparatively small lattice assembly some 5 or 6 ft cube for a low-enrichment graphite reactor, which is only about one-eighth of the volume (and cost) of an exponential assembly. This rather smaller assembly has some four times the neutron leakage fraction of the larger, and to produce the necessary 10^6 n/cm² sec thermal neutron flux level in the central test region requires a much larger input of neutrons from the source than is required to excite a flux of only one hundredth of this value required in the case of an exponential. For similar reasons of finer spatial resolution and greater leakage fraction the input to the water-moderated exponential experiment needs to be perhaps ten times that required in a graphite exponential and therefore needs the larger neutron input.

It has been found that the flux level can conveniently be met in graphite reactor fine structure experiments and even water exponentials by means of some thousand or so curies of radioactivated (gamma-emitting) antimony placed inside tubes of beryllium, but this type of source represents the economic limit of radioactive neutron sources; it is a very convenient type because it can be switched on or off at will simply by pushing the antimony out of the beryllium tubes into a shielded box. However, experiments of this type could equally well be carried out with a source reactor such as NESTOR, with the advantage of shorter irradiation times, the only disadvantage being the more restricted access to the experiments on account of the reactor's shut-down activity and any restrictions on the reactor's operation due to programmes of work in the other caves.

Once it becomes necessary further to increase the spatial resolution, as for the fine structure of water reactors, or to examine the space and energy distributions simultaneously in the low-enrichment graphite systems, yet higher neutron fluxes of some 10^7 n/cm² sec within the test volume become essential, and these can only be excited by means of the large output of neutrons available from a nuclear reactor or, possibly, a powerful accelerator type neutron source. The present neutron energy spectrum characterization techniques make use of ¼ in. diameter fission chambers, but it is projected to use fission chambers of half this diameter (Fig. 2) or less, which are therefore small enough to give quite good spatial resolution within the lattice cell structure in a gas-cooled reactor. These chambers are mounted at the ends of long tubes of the same diameter as the chambers themselves so that they can be pushed successively into holes drilled in the fuel and moderator regions of the lattice cell from outside the shielding around the assembly. The quantities measured are the ratios of count rates given by fission chambers chosen to have greater or lesser sensitivity to the various ranges of the low-energy neutron spectrum; for example, the ratio of the count rates given by a U^{235} coated chamber and by a Pu^{239} coated chamber placed successively in the same position in the lattice cell[6]. It is necessary also to measure the count rate ratio given by the same two chambers placed in a pure Maxwellian flux in a thermal column at some subsequent time in order to provide a calibration. Similar measurements using a U^{233} chamber paired with either of the two chambers already mentioned can produce further data, as can the ratios of the count rates obtained with each kind of fission chamber with and without a cadmium sheath. The net result of these measurements is to provide an effective temperature for the thermal group and a numerical factor which characterizes the relative intensities of the two groups of neutrons used in the two group reactor theory, and which together may be used to calculate the reaction rates which would occur with a given nuclide using its effective cross-section[7] for the appropriate temperature.

It may also be useful as an extension of the above type of work to examine the low energy neutron spectrum within a reactor lattice using a neutron chopper technique[3, 6]. In this method a small-diameter beam-hole is constructed within the lattice structure so that the neutrons emitted by a radiator formed by a chosen part of the lattice cell may travel down the beam-hole through the neutron chopper and into counting equipment synchronized with the chopper mechanism. Measurements of this type provide a much greater resolution of the detail of the

neutron spectrum than can be obtained by the simple two-parameter characterization referred to above but, on the other hand, this method requires even higher neutron flux levels within the equipment, of the order of 10^9 n/cm² sec, resulting in a much higher degree of activation of the lattice fuel and requiring the provision of a beam-hole within the lattice structure. The production of the necessary flux levels in externally positioned reactor lattices would require an operating power of 100 kW but development of the technique may lead to this type of experiment being useful at lower power levels.

The third class of intensive parameter experiment which it is intended to carry out with the NESTOR reactor requires a neutron flux intensity in the centre of the experimental assembly of some 10^8 n/cm² sec. Within this class fall two important types of measurements, namely those of the conversion factor and of the fast fission factor[9]. These two measurements can conveniently be carried out simultaneously in the one irradiation experiment although the subsequent nuclear measurements are somewhat different for the two quantities. In these experiments, which are concerned with nuclear transmutations within the fuel material itself, thin foils of aluminium are sandwiched between pairs of depleted uranium metal foils and inserted within the fuel rod in the positions of interest (Fig. 3). During the irradiation, fission processes occurring near the surface of the uranium foils result in recoil fission fragments becoming embedded in the surface of the aluminium foils, hence called catchers. Measurements of the radioactivity thus acquired by the aluminium can, with appropriate calibration, be used as a measurement of the rate of fission of U^{238} by fast neutrons. The fast neutrons concerned come from three main sources: directly from fissions occurring within the same fuel element, from fissions occurring within neighbouring fuel elements and by fast neutron reflection from the surrounding graphite back into the fuel element of origin. These three quantities can be distinguished from each other by suitable arrangement of fuel and moderator within successive experiments. Allowance must, of course, be made for the thermal fission occurring in the U^{235} remaining in the depleted uranium of which the foils are made.

The formation of plutonium within the depleted foils by neutron capture within the U^{238} can be measured by observing the 98 keV X-ray emission which occurs when the neptunium formed immediately after the U^{239} decays into Pu^{239}. This X-ray emission is measured using a scintillation counter and an energy discriminator. It is important to use depleted uranium for this measurement on account of the confusion otherwise caused by emissions from U^{235} fission products.

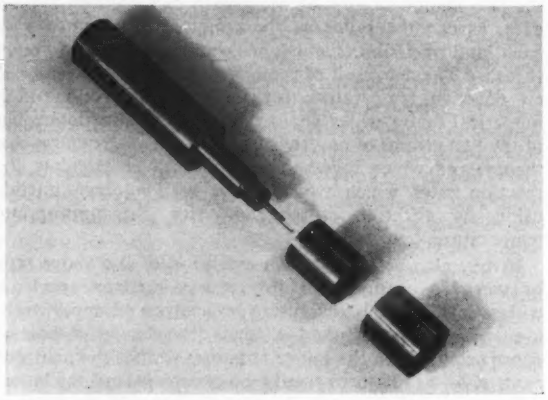


Fig. 3(a) Arrangement of eight foil-pack slots in uranium fuel element for fast fission factor and conversion factor catcher foil experiments. *Courtesy C. G. Campbell, AEE, Winfrith (From ref. 10).*

Fig. 3(b) Aluminium catcher foils and irradiated depleted uranium foils from eight positions of uranium fuel element (Fig. 3a) mounted for counting embedded recoil fission product activity and neptunium-plutonium 98 keV X-rays. *Courtesy C. G. Campbell, AEE, Winfrith (From ref. 10).*

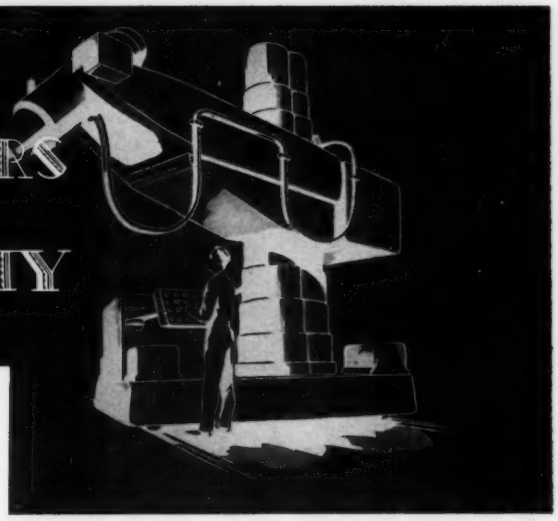
It is necessary for this experiment to make a simultaneous calibration measurement by exposing similar packs of uranium foils and catcher foils in a Maxwellian flux in a thermal column fed by the same reactor (to take account of source fluctuations). In this calibration the U^{235} fission rate: U^{238} capture rate is assumed known for a thermal flux from basic data.

In conclusion, it can be said that NESTOR will serve as a powerful source of neutrons for a very wide variety of sub-critical experiments upon many different types of power reactor. The foregoing discussion has referred mainly to uranium-graphite and to water moderated reactors, but in fact there is no limit to the variety of reactor types it may be used to study with the possible exception of the fast reactors or very small thermal reactors. The NESTOR cave system is so flexible that caves can be rebuilt, if desired, to be tailored to special requirements, but in their present 6 ft cube size they should suffice for a very wide variety of work including both room-temperature, uncontained systems and heated and contained experiments. The existence of a source reactor specially for this work will undoubtedly encourage the development of the relatively cheap sub-critical experiment wherever this will suffice in place of its critical more expensive counterpart.

REFERENCES

1. Cutts, B., *et al.*, "Graphite Moderated Thermal Reactor Calculations for the Calder Hall Reactors." *Proc. 2nd Gen. Conf.* 1958, Vol. 12, p. 612.
2. Campbell, C. G., and Grant, I. S., "Critical and Sub-critical Experiments with a Two-group Correlation of Results." *Proc. 2nd Gen. Conf.* 1958, Vol. 12, p. 728.
3. Kouts, H., *et al.*, "Physics of Slightly Enriched, Normal Water Lattices (Theory and Experiment)." *Proc. 2nd Gen. Conf.* 1958, Vol. 12, p. 446.
4. Hunt, C., AEE, Winfrith. Private communication.
5. Loosemore, W. R., *et al.*, "New Developments in Fission Chamber Detectors for Reactor Physics Measurements." *Proc. 5th Instruments and Measurements Conf.* (September 10–17, 1960). Also AERE R–3426, in preparation.
6. Campbell, C. G., *et al.*, "Measurements of Reactor Spectra." *Proc. 2nd Gen. Conf.* 1958, Vol. 16, p. 233.
7. Westcott, C. H., *et al.*, "Effective Thermal Reactor Neutron Cross Sections." *Proc. 2nd Gen. Conf.* 1958, Vol. 16, p. 70.
8. Campbell, C. G., and Freemantle, R. G., "Effective Cross Section Data for Thermal Reactor Calculations." AERE RP/R 2031 and supplements.
9. Poole, M. J., "Measurement of Neutron Spectra in Moderators and Reactor Lattices. I. Aqueous Moderators." *Journal of Nuclear Energy*, **5**, 3/4, p. 325 (1957).
10. Campbell, C. G., and Carter, M.D., "The Experimental Determination of Conversion Factors and Fast Fission Factors." AERE R/R 2397.
11. Campbell, C. G., and Carter, M.D., "The Experimental Determination of Conversion Factors." *Proc. Brookhaven Conf. on Resonance Absorption of Neutrons in Nuclear Reactors.* 1956, BNL 433.

ACCELERATORS IN RADIOGRAPHY



THE use of radiography in engineering as an actual step in production, rather than a laboratory refinement, probably dates from the early 1930s when fusion welding began to oust riveting in the manufacture of boiler drums. The trends of the last decade or so, towards increased pressures in steam and chemical engineering, as well as the peculiar requirements of the nuclear industry, have not only caused a tremendous increase in the amount of welding required but have, at the same time, necessitated thicker and more difficult welds and imposed stricter standards of quality. This, in turn, has resulted in an increase not only in the amount of radiography required, but in the penetrating power of the available facilities.

Industry has, for many years, been adequately served by conventional X-ray equipment which, for many purposes, will remain the most efficient and convenient method. There are certain classes of work for which isotopes would be both efficient and attractive from the standpoint of capital outlay, but conventional X-ray plant is probably more suitable for all-round application. There is, however, a growing need for machines which will undertake work which is outside the scope of conventional X-ray plant.

Limitations of Conventional Tubes

For those inexperienced in X-ray work, it should be borne in mind that the radiographing of thicker plates does not merely entail longer exposures; for a given machine there is a certain thickness beyond which radiography is not practicable.

Without delving into quantum mechanics, it is generally realized that the radiation given off by a body (for example, a tungsten target) struck by a fast electron, varies in wavelength according to the energy of the electron; the higher the electron energy (i.e., the higher the accelerating voltage applied) the shorter the wavelength and, therefore, the "harder" or more penetrating the radiation. It is important to bear in mind, however, that this is by no means a simple linear relationship; nor is the radiation produced at a single wavelength corresponding to the maximum voltage. A monoenergetic beam of electrons will produce a continuous spectrum of X-rays extending from very long wavelengths to a definite short wavelength limit which is inversely proportioned to the electron energy.

When X-rays pass through a steel plate, scattering takes place, the softer rays being more easily scattered. Since the scatter increases with thickness, it is easy to see why any given spectrum has a limit of plate thickness above which the proportion of scatter to penetration becomes so high that no amount of exposure will give practical results. It is possible to reduce the scatter factor (i.e., the ratio of scattering radiation to image-forming radiation) by increasing the tube voltage (Fig. 1). This, again, is by no means a linear relationship, but significant effects can be obtained over a certain range.

Unfortunately, conventional X-ray plant is subject to practical limits of voltage. Resonance transformer units have been built for 2MV and above, but the practical limits of conventional tubes and cabling are normally accepted to be in the region of 400 kVps.

There is one other important factor to be taken into account. In the same way as an absolutely sharp shadow can only be cast by a point source of light, high-definition radiographs can only be realized with a focal spot of the very small size. Extremely small focal spots also enable high definition even with short working distances, thus again reducing exposure; they also allow magnification by placing the X-ray film some distance behind the object.

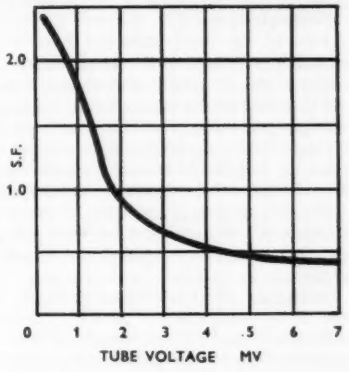


Fig. 1.—Reduction in scatter factor (i.e., ratio scattering/image-forming radiation) with increase in tube voltage. (*High Voltage Engineering Corp.*)

There are two basic methods of providing what may be termed "supervoltage" X-rays; first, by generating constant-potential d.c. at high voltage, and eliminating cable troubles by total enclosure of tube and generator, as in the **Van de Graaff** machine. Alternatively, by the use of indirect means of acceleration high-energy electrons can be produced without actually applying a corresponding high voltage; this class again can be subdivided into two types, the linear accelerator and the betatron.

Linear Accelerator

In a linear accelerator pulses of thermal electrons produced by a hot cathode are injected into one end of a waveguide supplied with r.f. power. To say that the electrons "ride on the backs" of the r.f. waves is, perhaps, over-simplifying the problem, but this is not the place to delve deeply into the theory of these appliances—we are more concerned with practical results—and it will suffice to say that the electrons are accelerated to the required velocity by means of the r.f. field which is set up by either a klystron or a magnetron.

Betatron

In a betatron, an evacuated toroid or "doughnut" is placed in an a.c. field so that electrons injected from a hot cathode

The illustration in the heading is an artist's impression of the Vickers 10 MeV linear accelerator.

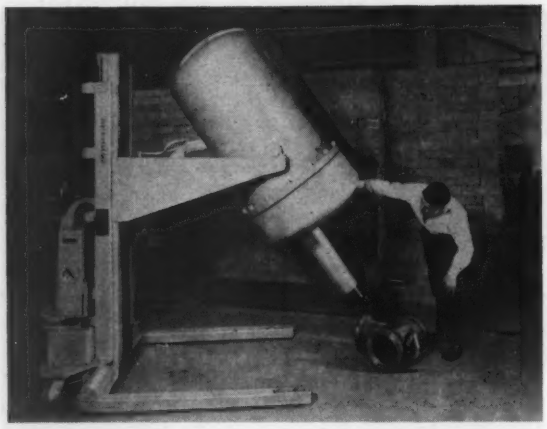


Fig. 2.—(Left) A 1MV Van de Graaff unit on simple fork-truck mounting.
(High Voltage Engineering Corp.)

system tend to take up an orbit around the centre of the doughnut, accelerating as the field increases. At the point of maximum velocity, an auxiliary pulsed field causes the orbit to expand or contract suddenly, so that the electrons strike a target which is just within or without (according to the design) the radius of the mean orbit.

H.V.'s VAN DE GRAAFF X-RAY UNIT

The Van de Graaff accelerator is well known in the irradiation and research fields; a typical installation was described in *Nuclear Engineering* for September, 1956, p. 250. As an X-ray generator it is available in 1MV and 2MV ratings, suitable for radiographing steel 5 in. and 10 in. thick, respectively.

One of the most attractive features of this machine is its compact self-contained arrangement since, apart from the control unit (a simple wall-mounted panel, in the case of the 1MV machine), it requires no external auxiliaries, the high-voltage generator, electron gun and X-ray tube being contained within a cylindrical housing, filled with gas under pressure to provide adequate insulation with small dimensions. The X-ray tube, originally of the pumped variety, is now sealed off, so that no external vacuum equipment is necessary. If required, the unit can be built into a fixed structure, or it can be slung from a crane, or mounted on a fork truck or gantry.

Mounting of the machine may take various forms. While the 2MV machine is usually gantry-mounted, the smaller dimensions and lighter weight of the 1MV machine make it suitable for a variety of mountings, including fork trucks or simple slinging, or even mounting on the end of a heavy steel tube to enable it to be placed right inside a long pressure vessel through a manhole.

The field of radiation is normally a 30° cone in the forward direction. The 2MV machine may be fitted with insert cones to reduce this angle; in the 1MV machine, the lead shield may be removed from the target extension, to permit circumferential radiation from the target for panoramic or all-round radiographs. General particulars of the two machines are given in Table 1.

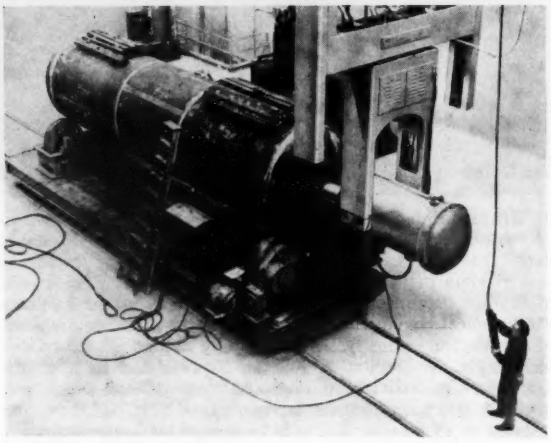
MULLARD LINEAR ACCELERATOR

The Mullard 4.3 MeV linear accelerator produces an X-ray output of about 600 r/min at 1 metre, and it is stated that

TABLE 1
Van de Graaff Machines

	1 MeV	2 MeV
Rating	0.01–0.25 mA	0.01–0.25 mA
Target current	8 r/min	60 r/min
Radiation at 1 metre	Less than 1 mm	0.75 mm
Focal spot diameter	5 ft 7 in.	7 ft 11 in.
Length: over tank	7 ft 8 in.	11 ft
overall	3 ft	3 ft
Diameter	2,500 lb	4,500 lb
Weight	0.6 in.	0.83 in.
Half-value layer (steel)	Better than 1%	Better than 1%
Sensitivity	2 kVA max.	3.5 kVA max.
Power required		

Fig. 3.—(Below) A gantry-mounted 2MV Van de Graaff unit radiographing a 10 ft seam in a 2¾-in.-thick pressure vessel, with a single 45-sec exposure.
(By courtesy of Allis-Chalmers Mfg. Co.)



radiographs of up to 14 in. of steel can be taken in a matter of minutes, with sensitivities of better than 0.5% (D.I.N. penetrameter) for plates over 4 in. thick, and better than 1% below 4 in.

Accelerator Unit

The actual accelerator unit is a corrugated waveguide approximately 1 metre long, fed with r.f. power from a magnetron, the electron injection being from a gun pulsed at the same voltage as the magnetron. The accelerator waveguide with its input and output feeds is enclosed in a vacuum envelope maintained at 3×10^{-6} mm Hg by a 4 in. oil diffusion pump. A special rotation joint allows the pump to remain vertical,

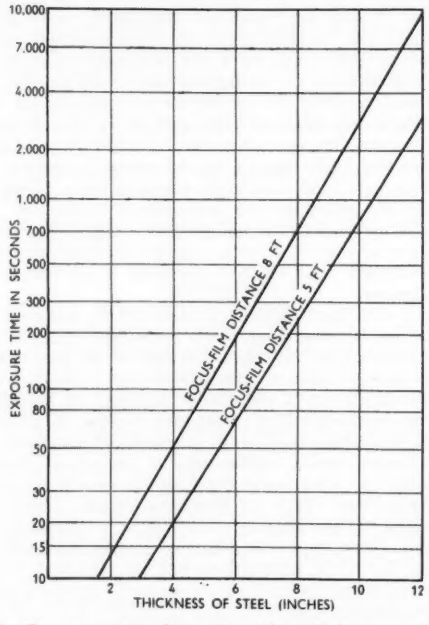


Fig. 4.—Exposure times for various plate thicknesses with the Mullard linear accelerator.

Fig. 5.—(right) A gantry-mounted Mullard linear accelerator.

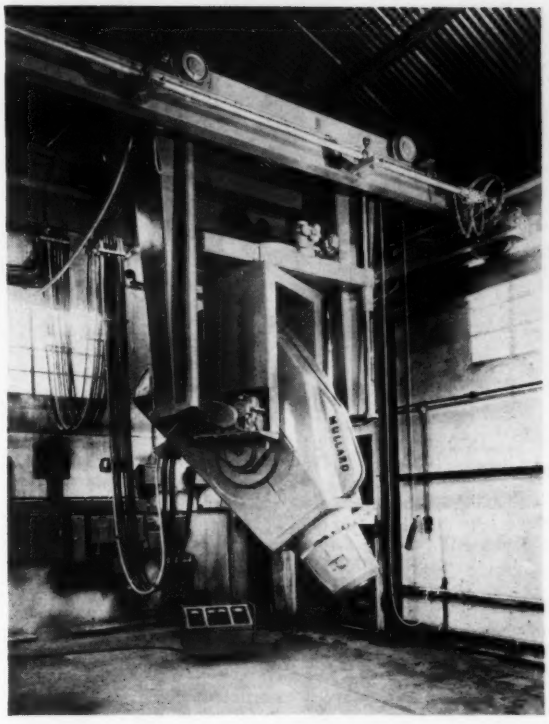
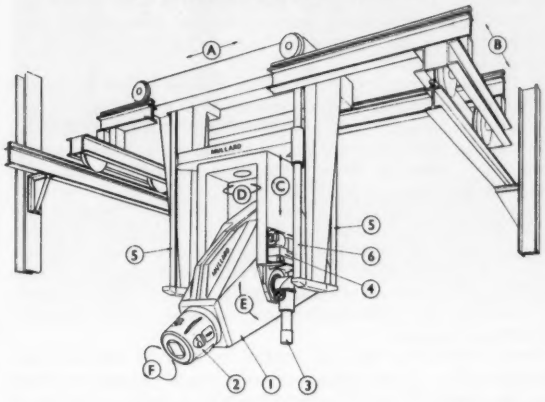


Fig. 6.—(below) Diagram of Mullard unit.
1, accelerator; 2, X-ray head; 3, diffusion pump; 4, backing pump; 5 and 6, lead screws and guide pillars for raising and lowering head. Movements (all motor-driven except F) A, traverse; B, long travel; C, vertical; D, 90° rotational; E, 90° angular; F, 360° rotational.



independent of the attitude of the accelerator. A rotary pump is provided for backing purposes.

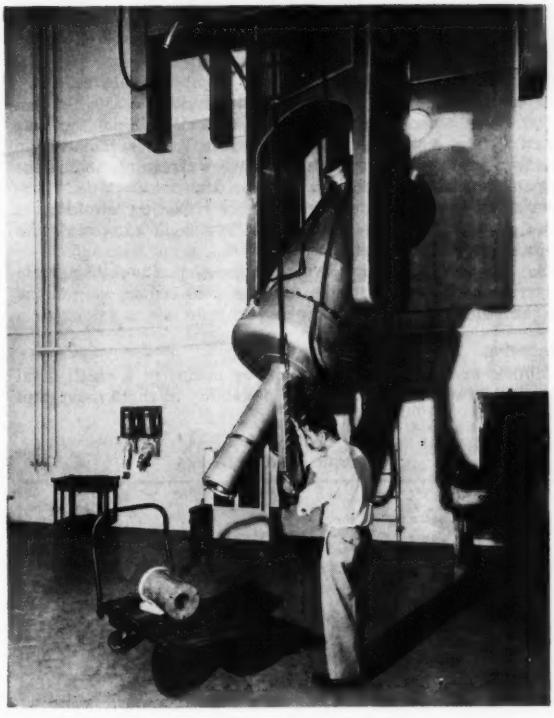
The gun is a diode pulsed at the same voltage as the magnetron. The cathode, which has an 8 mm filament of tungsten wire 0.3 mm diameter, is demountable, screwing into place with automatic focusing. Replacement of filament is possible within 5 min, by means of a vacuum gate valve which allows access without letting down the whole system.

R.F. Power System

The magnetron, with an average power of 2 kW, and a peak power of 2 MW, feeds the accelerator through a standard rectangular waveguide. A similar waveguide is also employed in a feed-back loop in which surplus r.f. power at the target end is recombined with the input end in a "rat-race" bridge. The waveguide system is separated by quartz windows from the evacuated input and output feeds of the accelerator, and is pressurized at 2 ats., to support high r.f. powers, any loss of pressure being detected by a pressure switch forming part of the modulator interlock system.

The modulator has a 3 ph transformer and bridge rectifier giving a maximum output of 700 mA at 12 kV. A 5 MW output pulse is obtained from a 2 μsec pulse-forming network, discharged through a hydrogen thyratron triggered by the pulse repetition frequency unit. The repetition frequency can be 100, 200, 400, or 500 pulses/sec.

Fig. 7.—A 2MV Van de Graaff gantry-mounted unit.
(High Voltage Engineering, Corp.)



X-ray Head

The target consists of a tungsten disc 5 mm diameter × 3 mm thick on which a spot 2 mm diameter is focused by a magnetic lens, a heavy alloy collimating cone restricting stray radiation from outside the 2 mm spot, to reduce the penumbra at the edge of the field. The cone on the target assembly is surrounded by a lead collimating cone. Beam defining diaphragms in the form of lead shutters 10 cm thick, can be adjusted in pairs to give a rectangular field; the shutters are designed so that the inner faces are parallel to the beam, to give further reduction in penumbra. The field can be adjusted

TABLE 2
Mullard Linear Accelerator

Rating	4.3 MeV
Radiation at 1 metre	600 r/min
Focal spot diameter	2 mm
Field at 1 metre: minimum	3×3 cm
maximum	25×15 cm (30×20 cm in special cases)
Wave guide length	1 m
Magnetron power: average	2 kW
Magnetron power: pulse	2 MW
Pulse frequency	100, 200, 400, 500 pulse/sec
Sensitivity: 2½ in. steel	0.9%
10 in. steel	0.34%
Electrical input	20 kVA
Cooling water	4.5 gal/min at 20° C
Weight of accelerator	1.3 tons

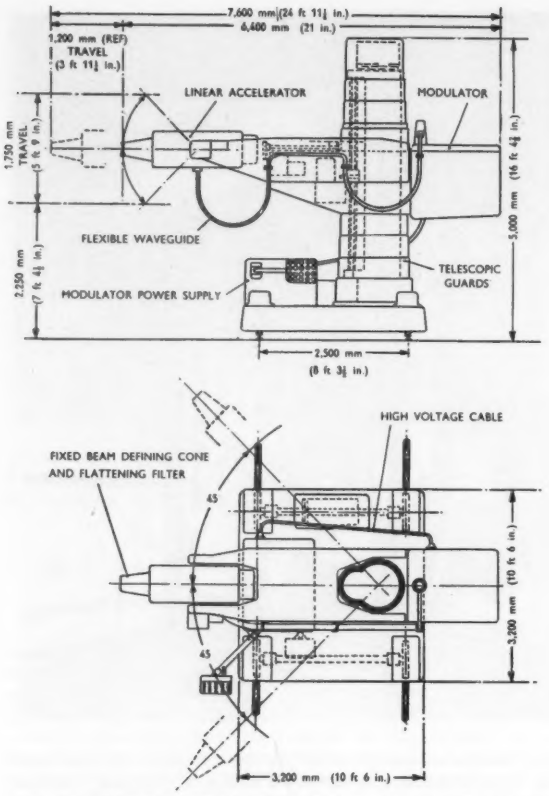


Fig. 8.—Elevation and plan of the Vickers linear accelerator.

from 3 × 3 cm to a maximum of 30 × 20 cm, at a distance of 1 metre, by finger-tip control, with scales showing field size.

The head contains duplicate ionization chambers for measuring dose rates, with quadrant ionization chambers for control of beam centring. A built-in light source is provided for setting-up purposes.

Mounting

The X-ray unit is housed in a steel container to guard against stray magnetic fields, and is mounted on trunnions giving 90° of tilt; these, in turn, are arranged to give 90° rotation about a vertical axis, and 8 ft rise and fall on a gantry with longitudinal and traversing movements. All movements are motorized, with push-button control. Other types of mounting can be provided, to suit site conditions. The auxiliary units, such as power supplies, modulator unit, controls, etc., are normally supplied in cubicle form. The power service required is 20 kVA 3 ph, 50/60 c/s, and the cooling water supply 4.5 gal/min at about 30 p.s.i. Further particulars are given in Table 2.

VICKERS LINEAR ACCELERATOR

The Vickers 10 MeV linear accelerator has an X-ray output of 7,500 r/min (at 1 metre), and is recommended for rapid radiography of steel thicknesses in the region of 12 in.

Accelerator Unit

The accelerator waveguide is 1.5 metres long, and is produced by an electroforming process, with a view to high dimensional accuracy and vacuum integrity. This is supported inside a coaxial stainless steel water jacket, which also serves as a former for the focus coils.

The high vacuum is obtained by means of titanium "getters." After breaking vacuum—for replacement of the electrode gun cathode—rough pumping to bring the vacuum within the range of the getters is carried out by a trolley mounted rotary pump.

The modulator, following established Vickers principles, is completely oil-insulated. It is divided into two units; a high-voltage d.c. supply which is mounted on the baseplate of the mounting, remote from the accelerator, and a unit containing all the pulse circuits of the modulator and the klystron, which is supported on the mounting proper, moving with the accelerator. The discharge of the modulator is by means of a Vickers pressurized spark gap; a simple demountable unit which only requires periodic replacement of the electrodes, by way of servicing.

R.F. power from a klystron of an average power of 7.5 kW with a pulse output of 5 MW is conveyed to the accelerator by a flexible waveguide which allows relative movement between the units in the horizontal plane, and permits the accelerator tube to be rotated in the vertical plane through 45° each side of the horizontal.

X-ray Head

The X-ray target is of tungsten, and is water-cooled, monitoring of the cooling water giving an indication of the performance of the accelerator. The small focal spot (2 mm diameter) is achieved by post-acceleration focusing, with powerful quadripole magnets.

Beam definition, and the control of leakage radiation are determined by a lead collimating cone, the semi-angle of which may be either 10° or 15° giving fields at 1 metre of 35 cm or

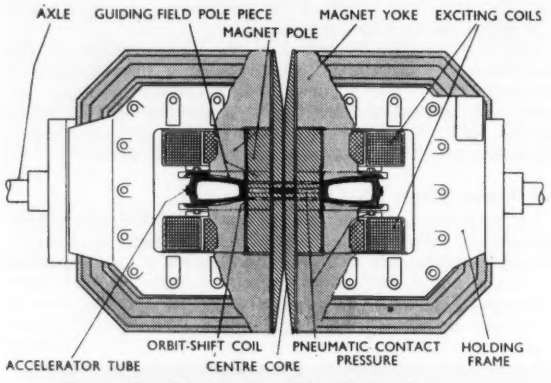


Fig. 9.—Simplified section of the Siemens betatron.

50 cm, respectively. In either case, an appropriate flattening filter is supplied, giving uniform fields of either 3,750 r/min or 2,500 r/min, according to the field diameter. Shielding provided by the cone is sufficient to reduce leakage radiation in the forward hemisphere to 0.1%; further screening behind the target reduces backwards leakage to the same value. It is considered that any attempt at further reduction would serve little purpose, since this value is already small compared with normal scatter from the specimen.

An optical range-finder giving the focus-specimen distance to better than 0.25%, and indicating the field centre, is mounted on the housing of the lead cone.

Mounting

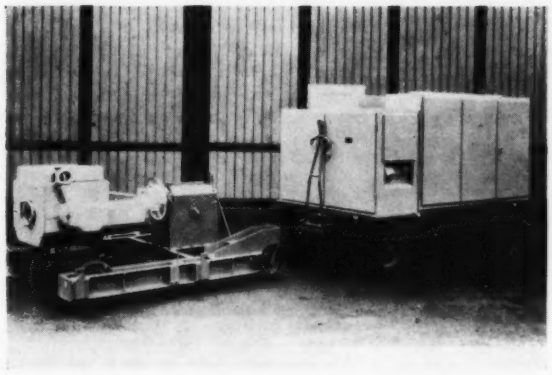
Efforts to obtain high definition by means of a small focal spot will be wasted if there is any possibility of slight movement

TABLE 3
Vickers Linear Accelerator

Rating	10 MeV
Radiation at 1 metre (unflattened)	7,500 r/min
(flattened), 50 cm dia.	2,500 r/min
(flattened)	3,700 r/min
Focal spot diameter	2 mm
Field at 1 metre	50 cm dia.
Klystron power average	7.5 kW
Klystron power pulse	5 MW
Pulse frequency	500/sec
Pulse duration	3 μ sec
Microwave frequency	2,856 Mc/s
Wave guide length	1.5 m
Weight of machine complete	30 tonnes

Fig. 10.—(right) Siemens betatron on "high-stand" mounting.

Fig. 11.—(below) Siemens betatron mounted on two trucks for mobile work.



during exposure, and particular attention has been paid to rigidity of mounting; the design of the unit is reminiscent of a radial drill.

A substantial cast iron baseplate of "egg-crate" construction is mounted on four 24 in. flanged wheels with solid axles and roller bearings so that it can travel along rails. This carries the vertical column, of cast iron, surrounded by a rotatable sleeve located at the top by a ball thrust race and, at the bottom, by a pressure-lubricated phosphor bronze bearing. The radial arm, of cast iron, can move vertically on the sleeve by a motor-driven nut and lead screw; in case of a failure, the arm is locked, and prevented from sliding down the sleeve. On one end of the arm is the tank containing the klystron and the modulator pulse circuits; the accelerator unit is carried on the other end of the arm on a sliding saddle. All movements are motor-driven, and all mechanisms are enclosed by telescopic guards and provided with pressure lubrication.

Further details of this machine are given in Table 3.

THE SIEMENS BETATRON

The Siemens betatron has a rating of 18 MeV and, in sensitivity tests, it has detected a wire 0.85 mm diameter through steel plate 300 mm (approximately 12 in.) thick. The arrangement can be seen diagrammatically in Fig. 9.

The accelerating field operates at mains frequency (50 c/s) and injection of electrons takes place immediately after the zero value of the positive half-wave, the initial energy being approximately 50 keV from a gun of special design, with a Wehnelt electrode which remains strongly negative and receives a brief positive pulse during the injection period. Acceleration takes place during the positive quarter-wave, during which the electrons travel about 1,000 miles, and the X-ray emission takes place at the maximum value of the quarter-wave, the orbit contracting under the influence of an orbit-shift pulse, and just grazing a platinum target, thus keeping the emission spot

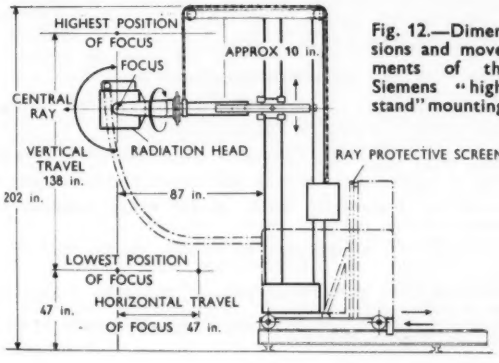
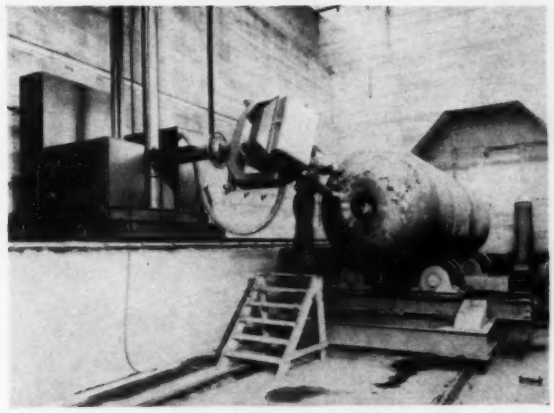


Fig. 12.—Dimensions and movements of the Siemens "high-stand" mounting.



very small. The ejection pulse timing is continuously variable to obtain an output energy from 3-18 MeV.

The doughnut, or toroidal tube, is of frequenta, a ceramic material, and is internally coated with a metallic film only a few microns thick, to prevent charges produced by scattered electrons interfering with the electron orbit. Grain-oriented silicon steel is used for the magnet assembly.

Mounting

In common with most devices of this type, the unit may be supplied with various mounting arrangements. Units have been supplied with the betatron on a type of "searchlight" mounting on a wheeled truck, together with auxiliaries such

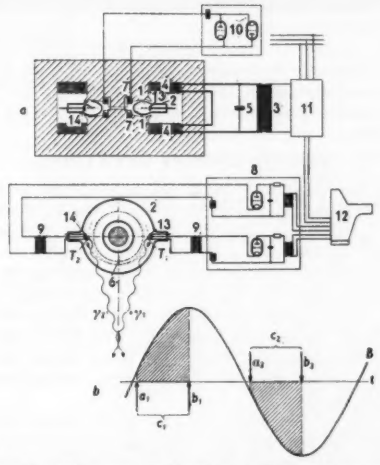


Fig. 13.—Diagram of the Brown Boveri betatron.

1, magnet pole; 2, doughnut; 3, transformer (6 kV); 4, exciter winding; 5, capacitors; 6, equilibrium orbit; 7, orbit-expansion coil; 8, impulse-circuit cabinet; 9, pulse transformer; 10, orbit-expansion circuit cabinet; 11, converter set; 12, control desk; 13, 14, electron guns; T_1, T_2, targets; γ_1, γ_2, twin beams; t, time; B, flux density; a_1, a_2, instant of electron injection; b_1, b_2, instant of orbit expansion; c_1, c_2, accelerating periods.

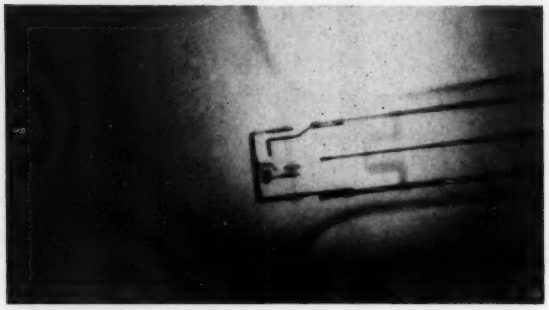
as blower, oil pump, etc. The electrical auxiliaries, including the regulating transformer and capacitors for the magnet, the high-voltage and pulse supplies, are accommodated on another low truck.

TABLE 4
Siemens Betatron

Rating	18 MeV
Focal spot	<0.3×0.2 mm
Half-value layer	33 mm
Sensitivity (110 mm steel)	0.5%
Electrical input	12 kVA
Weight of radiation head	Approx. 1 ton

Fig. 14.—(Left).—Gantry-mounted Brown Boveri betatron radiographing a Pelton runner.

Fig. 15.—(Below).—X-ray picture of the Brown Boveri gun and target assembly.



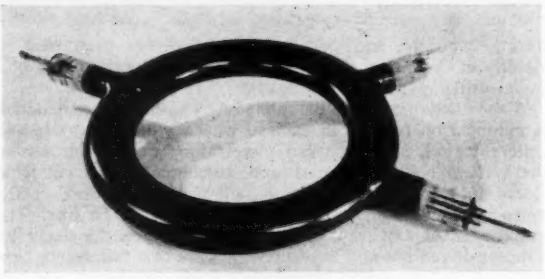


Fig. 16.—The Brown Boveri doughnut, showing twin guns and "getter."

Another method is the co-called "high stand" (Fig. 12) in which the betatron is trunnion-mounted on a horizontal arm which can be moved up and down a vertical pillar carried on a rail-mounted truck. In this case, the auxiliaries are all located on the truck.

BROWN BOVERI BETATRON

One of the most interesting features of the Brown Boveri design of betatron is the duplication of the electron guns and targets. Located on opposite sides of the doughnut, these operate on quarter-cycles of opposite polarity, so that two beams of radiation are produced. The two targets, 531 mm apart, are located so that the two beams are parallel or converge at 2.4 m. It is possible to operate with either beam energized, or with both beams simultaneously. In the latter case, the irradiated field is almost twice that for a single beam. With the beams converging, two stereoscopic radiographs can be made simultaneously.

The rating of this betatron is 31 MeV, and it is stated that radiographs are possible with steel up to 20 in. thick; it being possible to "see" a wire 0.03 in. (0.76 mm) diameter through 10 in. of steel. A wire penetrameter (DIN) sensitivity of 0.3% is obtainable between 6 in. and 14 in. thickness of steel. The small size of the focal spots (0.1 mm by 0.3 mm) enables a high degree of X-ray magnification to be used, which has been found to enhance flaw sensitivity.

At one metre distance the radiation intensity at the centre of the beam is of the order of 185/225 r/min (185 r/min is the guaranteed value). Copper equalizing filters are provided, giving a guaranteed field of 62 r/min flattened to within ±5% over a 200 mm (8 in.) circle. The intensities of the two beams are monitored by ionization chambers in the head, and automatic stabilization of beam intensity is available. Shutters in each beam control the beam height and light beams are provided along the axes of both beams for setting-up purposes.

Due to the very high energy used, the radiation is concentrated in the direction of the working beams, and stray radiation levels are low. The stray radiation is further attenuated by the iron magnet core and magnetizing coils surrounding the toroid, and is greatest in the plane of the electron orbit. In this plane, the stray dose rate at 90° to the working beams, and 5 m from the foci, is 200 mr/h, with both beams working.

TABLE 5

Brown Boveri Betatron

Rating	31 MeV
Radiation at 1 metre (unflattened)	185–225 r/min
(flattened)	62–72 r/min
Focal spot size	0.1 mm × 0.3 mm
Field at 1 metre	200 mm × 200 mm
Sensitivity (6–14 in. steel)	0.3%
Power consumption	16 kW
Weight of betatron and rotating frame	5.5 tons

Mounting

Various types of mounting can be arranged, to suit the requirements of the application. For fixed installations, the gantry type is generally suitable. That shown in Fig. 14 has horizontal and vertical movements, and rotation about horizontal and vertical axes, all being motorized, under push-button control. The auxiliaries, including the capacitor bank and equipment for electron injection and orbit expansion, are mounted on the gantry. For site work, mounting of the betatron head on a truck is suggested.

ACKNOWLEDGMENTS

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MULLARD EQUIPMENT, LTD., Mullard House, Torrington Place, London, W.C.1.
4 MeV linear accelerator.

PANTAK, LTD., 72 Alpha Street, Slough, Bucks, and Vale Road, Windsor, Berks.
Siemens Betatron.

VICKERS, LTD., Vickers House, Broadway, Westminster, London, S.W.1.
10 MeV linear accelerator.

WATSON AND SONS (ELECTRO-MEDICAL), LTD., Industrial Division, East Lane, Wembley, Middlesex.
Brown Boveri betatron.

Second Accelerator Conference

A report on the international meeting in Amsterdam, October 4-6, 1960

AN audience of more than 300 nuclear scientists and engineers from 24 countries attended the Second Accelerator Conference held in Amsterdam, October 4 to 6. The meeting, sponsored by High Voltage Engineering Corporation, Burlington, Mass., and its subsidiary in Amersfoort, The Netherlands, heard 22 papers on the use of accelerators in nuclear physics, particle research, radiation research and industrial application given by leaders in these fields.

A number of papers discussed the developments and the uses of tandem accelerators. Amongst them was that of Dr. P. H. Rose of High Voltage concerning the new three-stage tandem with which beam currents of 10 mA and energies of 30 MeV may be achieved within the next 10 years. Dr. Rose expressed the opinion that of the two possible beam injection systems (negative ion and neutral beam) the neutral beam held the greatest potential. From an initial 10 mA of positive ions a target current of 191 μA of protons is theoretically possible. Tests at an energy of 15 MeV with a beam of 30 $\mu\mu$A had shown a stability of one part in 100,000.

The first of HVEC's tandem accelerators became operational at Chalk River in February, 1959, and Dr. Gove of A.E.C., Ltd., reported that in the 18-month period since then utilization had been about 80%. The Aldermaston machine was also discussed by Dr. Allen in relation to the experiments that have been pursued at AWRE.

Recent advances in high-power microwave electron accelerators for physics research were discussed in a paper by J. C. Nygard of High Voltage and Dr. R. F. Post of the University of California.

"There have been some significant steps forward in the microwave accelerator art, which is indeed fortunate, for the electron linear accelerator is an ideal tool for neutron and photonuclear physics in the energy range from 15 to about 200 MeV," Mr. Nygard said.

"The search for further fundamental knowledge in the fields of nuclear, atomic and molecular structure continues with increasing demands for experimental versatility, precision and power. Much of the existing useful data in this energy range has been obtained with orbital accelerators of limited power output. As a consequence, the experimental substantiation of theoretical understanding of photonuclear interactions and other interactions is lacking in detail. To obtain data indicating more than general effects, we require at least one order of magnitude improvement in accelerator precision and several orders of magnitude improvement in experimental yield or power output from the accelerator."

The authors described several very high current linear accelerators of great precision including:

(1) A 10 MeV synchrotron injector having 200 mA of pulse current with an energy spread of 1% and a divergence of less than 1 m radian.

(2) A 35 MeV machine with pulse currents up to 500 mA and 30 μ sec pulse length offering 2×10^{12} neutrons per pulse.

(3) A new 130 MeV linear accelerator for the U.S. National Bureau of Standards.

An important breakthrough in the problem of "beam blow-up," together with its possible origin in TM 110 mode excitation, was reported. New accelerating structures have been employed to advantage in the elimination of this problem. The attractive features of the new and potentially useful RF tube called the Amplitron, a Raytheon product, were also described.

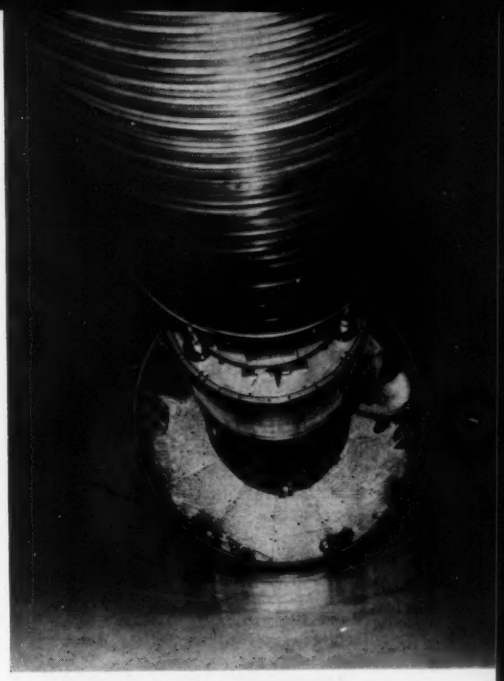
Mr. Nygard and Dr. Post concluded that techniques are now available for microwave linear accelerators of arbitrarily great precision and power output.

Earlier in the conference, Dr. L. Katz of the University of Saskatchewan, Canada, had set up several interesting and formidable targets for manufacturers of linear electron accelerators for nuclear research. Dr. Katz explained that the "linac's" versatility, particularly, makes it an ideal research tool for smaller research organizations. "I would place reliability at the head of my list of requirements," Dr. Katz said. "I want to be able to flip a switch to turn the machine on, then go ahead with the research." On the subject of pulsing, he said linear electron accelerators now being designed for neutron time of flight work should consider pulses of 1/10 n sec duration with repetition rates of about 10^6 pps.

In a session devoted to industrial applications of radiation, Dr. S. H. Pinner of B.X. Plastics, Ltd., in England, and W. H. T. Davison of Tube Investment Research Laboratories, also in England, reviewed the development of radiation process applications and pointed to some promising areas for further development.

They noted that the patent literature discloses well over 200 U.K. and U.S. patents on radiation processes, which can be classified into (a) polymerization, (b) crosslinking of polymers, (c) degradation of polymers, (d) multicomponent polymers (graft and block copolymers), (e) general chemical reactions and petroleum products, (f) sterilization, (g) specific articles and shapes, (h) inorganic compounds, (i) machines for generating radiation, including isotopes.

Processes involving polymers account for more than 70% of these patents, so it can be fairly claimed, the authors said, that the major application of radiation will lie in the polymer field. The first polymerization patent was granted in 1927 and the first crosslinking patent in 1933, but the first patent on multicomponent polymers was only granted in 1958, a field which the authors discussed at length.



At Aldermaston the U.K. AEA's 12 MeV tandem Van de Graaff accelerator for fundamental research into the structure of the nucleus.

The development of multicomponent polymers can be classified into (1) direct grafting, (b) indirect grafting, (c) peroxidation grafting, (d) block copolymers, and (e) attenuated network polymers, according to Dr. Pinner and Mr. Davison.

More recently, they said, the application of radiation processes to polyvinyl chloride has attracted interest. This can be converted into infusible and insoluble rigid sheet with potential use as a solvent and corrosion resistant structural material, by incorporating a plasticizer containing two or more olefinic double bonds and subjecting to radiation. The plasticizer is caused to polymerize and form a network which is attenuated by the polyvinyl chloride molecular chains.

They noted that one drawback to this material is its brittleness, but recent work has shown this can be overcome by incorporating a small amount of a saturated elastomer. By inference, they pointed out, well-crosslinked materials are not necessarily brittle and this widens the scope for attenuated network copolymers in industrial applications.

Later in the same session, Mr. D. Moore of the Medical Research Council, Hammersmith Hospital, London. discussed neutron, electron and X-ray beams for radiation research, and Mr. D. A. Trageser of High Voltage Engineering previewed future accelerators as intense sources of radiation for processing. He described developments which will lower the unit cost of radiation power below $1/kWh under a wide variety of design criteria.

Electrostatic Generators

Colloque International sur la Physique des Forces Electrostatiques et leurs Applications

AN International Colloquium, held under the auspices of the Centre National de la Recherche Scientifique, took place at Grenoble from Sept. 24 to Oct. 1. The subjects discussed covered the generation of electrical power by electrostatic means and the applications of the machines used. It is believed to have been the first international conference devoted entirely to the science of electrostatics. Due to the presence of Professor Felici, who is the holder of the Chair of Electrostatics at Grenoble University, this was a natural meeting place and more than 120 engineers and physicists gathered there to hear the lectures and join in the subsequent discussions.

Appropriately, after a description of the early days of electrostatic machines in Grenoble, given by Professor Neel, the lectures were inaugurated by a talk by Professor Felici on the types of electrostatic generator and his hopes for the next generation of electrostatic machines. This, in conjunction with a talk by Professor Trump of Massachusetts Institute of Technology, indicated in broad outline the scope of present possibilities and the problems of the future. There are two types of electrostatic generator in current use; the Van de Graaff belt type machine and the Felici insulating transporter cylindrical machine. Both have their advantages and disadvantages. Briefly, for high voltages and very low currents the Van de Graaff is better and for low voltages (below 1,000,000 V) and higher currents (up to 50 mA) the Felici machines are better. For long-term continuous running, the cylinder machine would appear to be more reliable but in its present state of development it cannot provide the very high voltages or current that may be required.

In Professor Trump's talk, he discussed a further type of electrostatic generator, the disc machine. This is not a new development and on show at the Colloquium was a very early disc type generator built in the late 1940s at Grenoble. However, it seems to be generally agreed that this type of design has the greatest development possibilities, particularly for space travel where the problem of insulation is much reduced.

Several papers were presented which discussed the application of this type of electrostatic generator for ion propulsion, as considerable research is being carried out both in France and the U.S.A. on electrostatic machines for this purpose. The design of a generator delivering 1,250 kW at 200 kV is being studied at HVEC in Massachusetts and parallel studies are proceeding in France.

The future development of the cylinder machine is being studied to increase the currents available and other dielectrics, including various liquids, are being studied. Questioning elicited visualized requirements of 100 kV at 100 mA to 1 MV at 1 amp but no concrete suggestions as to how this might be achieved were agreed.

On a subsequent visit to the factory of SAMES in Grenoble, the members of the Colloquium were able to see the ideas of Professor Felici in concrete form. Of particular interest also on the nuclear side were the neutron generators capable of delivering fluxes of neutrons up to 10^{11} n/sec. Continuous development aimed at greater fluxes with smaller machines is being carried out.

Future applications in the nuclear field would appear to lie with neutron sources of higher fluxes than are at present available. If fluxes of the order of 10^{12}-10^{14} n/sec could be produced economically, there would be a demand from those at present forced to use reactors for activation experiments. There is some argument as to what an economic figure might be but there is a real hope that an accelerator working at, say, 1 MV with 4 mA of ions in the beam and a beryllium target could produce a flux of 10^{13} n/sec. From preliminary inspection it was severally agreed that the price of such a machine might be very attractive *vis à vis* a small reactor.

Correspondence

Power Reactor Simulation

Sir,—With reference to the article "Simulating Power Reactors" by D. P. Markham in your September issue, I should like to point out that the logarithmic simulation described has certain limitations when representing a rapid decrease in reactor power. In these circumstances, the scaling difficulties which have been avoided for P by the logarithmic transformation, may reappear in the scaling of the delayed neutron quantities.

Since x_j is defined as the ratio of delayed neutron emitters to reactor power, a rapid fall in P can demand an increase in x_j by the same factor.

From equation (8) in the original paper, we have

$$x_j = \frac{c\mu_j - \frac{dx_j}{dt}}{\frac{d}{dt}(\log P) + \frac{1}{\tau_j}} \qquad (1)$$

Suppose that the reactor power is decreasing exponentially,

$$P = P_o \exp(-t/T) \qquad (2)$$

where T is the time for the power to decrease by a factor e then $\frac{d}{dt}(\log P) = -\frac{1}{T}$, and when x_j has reached a steady value $\frac{dx_j}{dt} = O$

Substituting in (1) gives $x_j = c\mu_j \tau_j/(1 - \tau/T)$ (3)

As $T \to \infty$ (steady reactor power) $x_j \to c\mu_j \tau_j$ which will be its quiescent value. If the scaling has been chosen so that this value is a factor m below the overload point of the computing unit concerned, then the most rapid continued decrease in reactor power without overloading is given by:—

$$\frac{1}{1 - \frac{\tau_j}{T}} = m \quad \text{or} \quad T_{\min} = \frac{m\,\tau_j}{m - 1}$$

and this criterion must be satisfied for all delayed neutron groups.

For a rapid step reduction in power ($T \ll \tau_j$) equation (3) is invalid. However, there will be no immediate change in the actual number of delayed neutron emitters and so x_j must increase by the same factor as the step reduction in power, which must therefore not exceed the "safety" factor m on the scaling of the delayed neutron qualities.

G.J.R.M. (English Electric Aviation, Ltd.).

The above comments refer to only one of a number of problems facing the designer when seeking a satisfactory simulation. The scaling of the various parameters is very important and is affected at one end of the scale by the considerations pointed out and at the other by the need for high resolution for one or two particular parameters. A suitable compromise has to be established to obtain the desired results throughout the range of parameters concerned. D.P.M.

Industrial Notes

100-ton Butters monotower crane.

Butters Bros. have recently handed over the first of two 100-ton electric travelling monotower cranes. Although the cranes are primarily intended for shipbuilding, the company point out that many engineering construction companies are likely to be interested in a machine lifting 100 tons at a radius of 122 ft.

Following the announcement of the formation of the new company **Leybold-Elliott** by Elliott Brothers (London) and Leybold of Cologne, an exhibition was held on September 28 to show the range of high vacuum industrial process equipment which is to be marketed and manufactured by the new company.

The Institution of Nuclear Engineers held its inaugural dinner at the Savoy, London, on October 3. Guest of honour was Sir Alexander Fleck. The Institution now claims some 700 members.

Allis Chalmers have acquired a controlling interest in Etablissements de Constructions Mecaniques de Vendeuvre, S.A.

Alcan Industries is the new name for Northern Aluminium. The trade name, Noral, will be continued.

Teleflex Products are to supply damper gear and window control equipment for Berkeley and for the Zero 2 building at Winfrith.

Personal

Appointments

Professor Gueorgui Nadjakov of Bulgaria as president of the Conference of the IAEA.

Mr. H. F. Akehurst, Mr. R. M. Fairfield and **Mr. W. C. Handley,** as assistant managing directors of B.I.C.C. **Mr. E. Bowyer** and **Mr. C. H. B. Pipkin** as executive directors.

Mr. Gordon Jackson, chairman, **Maj.-Gen. G. D. G. Heyman** and **Mr. G. M. R. Lord,** joint managing directors and **Mr. Adrian Legg** and **Mr. S. McLennan** as directors of A.M.F., Ltd.

Mr. H. E. C. de Chassiron to the board of D. Napier and Son.

Sir Donald Perrott to the board of J. A. Stirling.

Mr. J. A. Kilby and **Mr. A. Reid** to the board of Colville Constructional Company.

Mr. George A. Smith to the board of the Electronic and Equipment Group of the Plessey Company.

Mr. A. H. Hird, Dr. C. F. Bareford, Messrs. W. D. Opher, W. D. Pugh, L. Redshaw, S. P. Woodley, R. P. H. Yapp and **A. D. Read** to the board of Vickers Research.

Mr. J. M. Mitchell and **Mr. M. J. S. Clapham** to the board of Almin.

Mr. W. Brining, Mr. J. M. Graham, Mr. J. M. Mitchell and **Mr. S. W. Weysom** to the board of Imperial Aluminium Co.

Mr. A. G. Herring to the board of Brookhirst Igranic.

Mr. L. M. T. Castle and **Mr. N. C. Macdiarmid** to the board of the Staveley Iron and Chemical Company.

Mr. Alfred Ratcliffe to the board of Metals Division, Imperial Chemical Industries.

Lieut. Cdr. R. B. Lakin to the board of Vickers-Armstrongs (Engineers).

Sir Richard Snedden to the board of the Superheater Co.

Mr. Norman J. Travis as deputy managing director of Borax Consolidated.

Mr. Richard Miles as chairman of Joy-Sullivan.

Mr. R. S. Glaister as customer liaison engineer at Panellit, Ltd.

Professor B. Bleaney, F.R.S., and **Dr. J. W. Cook, F.R.S.,** as members of the Council for Scientific and Industrial Research.

Mr. J. V. Sheldon as sales director of Simplifix Couplings, Ltd.

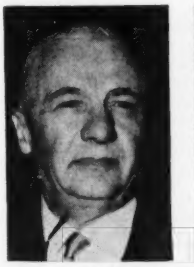
Messrs. H. H. E. Beck, J. V. Sheldon, L. H. Sheffield, S. T. Wise to the board of British Ermeto.

Mr. D. R. S. Turner as director and general manager of Davidson and Co., Ltd.

Mr. P. B. Ades and **Mr. B. J. S. Totlow** to the board of Airmec.

Air Marshal Sir Geoffrey Tuttle as a member of the board of Vickers-Armstrongs (Aircraft).

Mr. C. E. Wrangham to the board of Simon-Carves.



Prof. G. Nadjakov.

Mr. G. Jackson.

Mr. A. P. Taber.

Mr. P. B. Ades.

Overseas

Will Mitchell, Jr., as acting director, Research Division, Allis-Chalmers Manufacturing Company. **R. C. Allen** named senior engineering consultant; **L. J. Linde** to head new engineering service group; **W. W. Edens** as assistant director of research.

Sir Kenneth Hague as chairman of Babcock and Wilcox of Africa (Pty.).

Arthur L. Adamason as chairman of the board and chief financial officer of Electronic Associates Inc.

Alden P. Taber as vice-president of the Babcock and Wilcox Co., New York.

Allan Douglas McKnight, Executive Commissioner of the Australian AEC as chairman of the IAEA's board of governors.

Mr. Jack Gibson as managing director of the Consolidated Pneumatic Tool Co. S.A. (Pty.), Ltd., Johannesburg.

Dr. Kenneth S. Pitzer as chairman of the General Advisory Committee and **Casper W. Ooms** as chairman of the Patent Compensation Board of the U.S. AEC.

John L. Kuranz as chairman of membership committee of American Nuclear Society's new Isotope and Radiation Division.

Resignations

Sir Ronald Scobie as director of British Insulated Callender's Cables.

Mr. Harold Melhuish from the board of of the Superheater Co.

Mr. E. J. Earnshaw from the board of the Plessey Co., Ltd.

Tours

Philip W. Faulconer of the University of California Lawrence Radiation Laboratory is to tour world scientific institutions. He will visit Japan, India and Europe observing research facilities at universities, nuclear power establishments and industrial laboratories.

Obituary

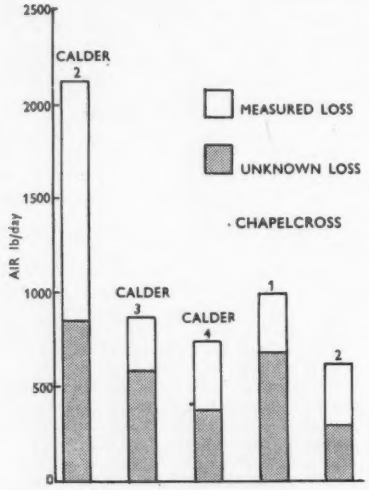
Nuclear Engineering records, with regret, the death of **Lord Simon of Wythenshawe.** He was president and former chairman of Simon-Carves and Henry-Simon (Holdings).

Technical Papers and Publications

THE INSTITUTION OF MECHANICAL ENGINEERS

Leak Tests on Calder-type Reactors. By J. K. Smith (Senior Design Engineer, D. and E. Group, U.K. AEA), and J. Cheetham (Reactor Group Engineer, Kennedy and Donkin).

Coolant leakage on gas-cooled reactors has turned out to be considerably higher than was expected, the first reactor at Calder losing some 2 tons/day of CO_2. This figure has been reduced to 2,500 lb/day on Calder 2, and to 600 lb/day on the 6th reactor (Chapelcross 2). Although even this latter figure may seem high, it is seen in clearer perspective if it is realized that the leakage through a hole 0.075 in. diameter, with CO_2 at 100 p.s.i., would be 1,200 lb/day, so that the Chapelcross leakage is equivalent to a pinhole in a gas system containing 450 valves, 650 flanges between 3 in. and 54 in., and more than 200 screwed connections. These figures do not include the burst slug detection system, which introduces a further 40 miles of piping and 17,000 joints.



Air losses during tests at 140°C.

This paper describes at some length the test programme devised to discover and rectify leaks in gas circuits using compressed air and a number of different techniques including bubble tests with soap and glycerine; loss-of-pressure tests; and, using CO_2 instead of air, infra-red gas analyser techniques.

Throughout, it has been found that there is a loss which can only be written off as "unknown." Tests on a simpler circuit (i.e., the by-pass cyclone circuit) have shown that even if examined and found "leak-free" with soap solution, a pressure drop of 2 p.s.i. in 24 hours could occur. It appears that there is a "seepage" rate which cannot be detected by practical means, nor can it be rectified.

A number of recommendations are made for improving the general gas-tightness of reactor systems, which will be of interest to reactor designers. The main object of the paper, however, is to indicate test methods for those concerned in proving circuits after construction.

Pipe Ranges for Water at High Pressures and High Temperatures with Special Reference to Boiler Feed Systems. By K. B. Jacob, M.I.Mech.E. (Babcock and Wilcox Ltd.)

Pressures now used for power station feed water circuits tend to result in excessively stiff piping runs, and the thermal expansion of the pipes may be severe enough to cause actual distortion of feed pump bodies. The paper reviews possible methods of increasing the flexibility of feed pipelines, including the reduction of pipe bore by increase of the velocity (subject, of course, to limitations due to water-hammer and pressure drop) and by providing proper anchoring and expansion arrangements.

Suggestions are also given for a reduction in pipe wall thickness to limits imposed by a safe working stress for available materials. It is considered that in many cases existing formulæ are over-generous; notably, in allowance for corrosion. It is pointed out that modern boilers require—and get—treated water of a quality which could not cause corrosion in the pipelines.

U.S. AEC

TID-3556. Selected Reactors of the Power Reactor Demonstration Programme. A Literature Search. Compiled by James M. Jacobs. (Office of Technical Services, Department of Commerce, Washington 25, D.C. $0.75.)

A list of reports and technical papers on 10 selected reactors of the Power Reactor Demonstration Programme, including Elk River; Enrico Fermi; Florida; Hallam; Parr Shoals; Pathfinder; Piqua; Puerto Rico; Saxton; Yankee. Availability as normal copy, photostat, and/or microcard, is included.

ACNP-5920. Pathfinder Atomic Power Plant. Coolant Distribution Tests. By J. Wilson and R. Styles (Allis-Chalmers). (Office of Technical Services, Department of Commerce, Washington 25, D.C. $0.75.)

This report covers tests to determine the head loss coefficient through the inlet plenum of the Pathfinder reactor and to determine the flow distribution among the fuel element nozzles for various operating conditions (i.e., with all three pumps operating at the same flow rate and with any combination of only two pumps operating at the same flow rate). The tests were carried out on a quarter-scale wooden model of the Pathfinder, using air as a working fluid and traversing pitot tubes for measurement.

The loss coefficient was determined to be 1.8 ± 0.3 and the velocities of flow through the fuel element nozzles were determined as being within $\pm 5\%$ of average flow with all pumps operating, and within $\pm 10\%$ of average flow when only two pumps are operating.

ACNP-5922. Pathfinder Atomic Power Plant. Conceptual design study of CRBR quick-operating pressure vessel closure and self-energizing seal tests. By R. G. Michel (Allis-Chalmers). (Office of Technical Services, Department of Commerce, Washington 25, D.C. $3.00.)

This report details, in something like 170 pages of typescript, the work carried out by Allis-Chalmers Manufacturing Company and two sub-contractors, Allstates Design and Development Company Inc., and Koerper Engineering Associates Inc., on the development of a quickly removable head for the Pathfinder reactor. Some idea of the magnitude of the problem may be obtained from the operating requirements, which are as follows: a clearance opening of more than 7 ft, capable of containing saturated steam at 500°F and 600 p.s.i., with a leakage rate not exceeding 5 lb a day from the primary seal (if a secondary seal is used). The locking and sealing devices to be capable of withstanding the pressure and temperature for about four months over a design life of 20 years, i.e. three to four openings per year. The locking mechanisms to be suitably insulated and sealed from contact with the shield pool water above the reactor, yet capable of being opened under 18 ft of water (i.e. remotely), the opening and closing period being less than 30 minutes. At the same time heavy metal sections in the head region to be avoided, since the cooling from operating temperature to shut-down temperature had to occur in about one hour without excessive thermal stress. Finally, the closure design should include a suitable indexing device so that the control rod drives were suitably positioned.

A large part of the programme was devoted to investigations of suitable self-energizing seals (by "self-energizing" is meant one in which the operating pressure itself tends to tighten the seal). While Teflon (polytetrafluorethylene), either virgin or asbestos-impregnated, would appear to be the most feasible material for seals, several disadvantages occur, including high shrinkage rates and severe radiation damage.

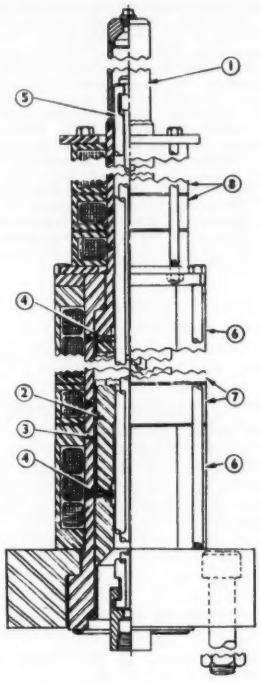
While many ingenious ideas for quick operating closures are detailed in the report, the conclusion arrived at is that all of them tend to become complex in design, operation or manufacture; the complexities primarily arising because the closure must not only contain the internal pressure of the vessel but also prevent shield pool water from coming into contact with the head. In addition, extensive evaluation programmes will be necessary to select low-friction, non-galling materials for threaded locking rings or sliding wedge-locks and, particularly, seal material. It is considered, therefore, that the number of evaluation studies that must be carried out before development can proceed on any particular design cannot be included in the CRBR programme and the success of a concentrated development effort without benefit of such data would be

unpredictable. It is therefore not recommended to proceed with the development programme for a quick operating closure.

ANL-6073. Advanced Designs of Magnetic Jack-type Control Rod Drive. By Joseph N. Young (Reactor Engineering Division, Argonne National Laboratory). (Office of Technical Services, Department of Commerce, Washington 25, D.C. $3.)

This report covers the developments made since a previous report ANL-5768 (December, 1957). It is stated that there have been no basic changes because there have been no mechanical problems arising. A description of minor modifications is given, together with an account of the development of higher-pressure models.

One of the most interesting portions of the report is a discussion on thick versus



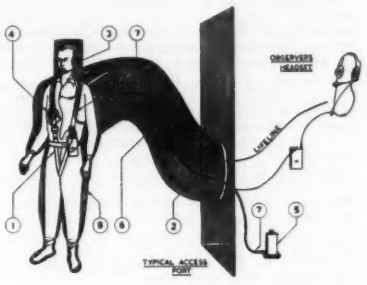
High-pressure magnetic jack. 1, pressure shell; 2, armature; 3, non-magnetic sleeve; 4, cushion washer; 5, drive rod; 6, move coil; 7, grip coil; 8, hold coil.

thin pressure shells for high-pressure work. It is stated that the idea of using a thin pressure shell is a carry-over from canned-rotor motors, the only real advantage being avoidance of non-magnetic sections which require a considerable amount of welding. Actually, it is pointed out that a thick pressure shell is an advantage since the magnetic sections, if they are thick enough, spread out the flux, thus reducing the radial forces on the armature. It is stated that the welding problem has been minimized by the use of a new weld material and by the fact that a thick pressure shell has, of course, lower stresses due to pressure. An account is given in an appendix of the design and construction of a thick-shelled jack for an operating pressure of 2,600 p.s.i. (design pressure 3,200 p.s.i.). For the magnetic sections stainless steel AISI type 430 was selected, with Inconel for the non-magnetic section. The weld metal was Inco-weld A.

U.K. AEA

AERE ES/R2674. Decontamination Suit. (The "Newt" Suit). By W. K. Curtis and D. W. Kingston (Harwell). H.M.S.O., 5s.

Tests are described on a simplified form of suit for working in contaminated areas. With the well-known "frogman" type of suit it is necessary for the operator to be cleaned externally before undressing and then for the suit to be thoroughly decontaminated. The "Newt" suit as it is termed normally remains in the contaminated area, and the operator enters and



The "Newt" suit. 1, safety harness; 2, clamping ring; 3, headphone/microphone; 4, mask; 5, filter; 6, hose; 7, hose clip; 8, suit.

leaves via a tunnel, of the same material as the suit, which is sealed to a large port in the cell wall. When it is required to replace the suit this may be carried out in the same way as a glove or transfer bag in a glove box.

The report describes trials of air supply, robing, disrobing, rescue, working conditions and suit disposal. There are two methods of entry into the suit, one being by doubling back the tunnel on itself (i.e. turning it half-way inside out) and then rolling back in a ring until the suit is close up against the port. This is not practicable when the depression in the cell is more than 1¼ in. w.g. The other method is to allow the suit and tunnel to be drawn full into the cell and to slide down the tunnel feet first.

The main features of the equipment are shown in the diagram. It will be noted that the operator wears safety harness so that in the event of being overcome by heat he can be rescued with reasonable ease.

The report deals very fully with details, including materials, ventilation and communications, and the work which it is possible to carry out in the suit.

AERE R3101. Critical assemblies of aqueous uranyl fluoride solutions. HAZEL. Part 4: Fuel recovery. By J. Hornby, D. Walmsley, G. P. Wall and E. A. Talbot (Harwell). H.M.S.O., 2s. 6d.

Describes the methods by which valuable materials were recovered from the solution used in the homogeneous aqueous reactor HAZEL after dismantling. The operating solution consisted of U^{235} in the form of enriched uranyl fluoride in heavy water. Three methods were considered for the separation, including ion exchange and evaporation of the heavy water in a climbing film evaporator. Both of these were discarded in favour of batch distillation and the report describes the design, commission and operation of the recovery still. More than 99.9% of the uranyl fluoride was recovered, and 99.79% of the heavy water. It is interesting to note that the work was carried out in seven months and the total cost was less than 5% of the value of the material recovered.

AERE R3274. The Removal of Cs^{137} and Sr^{90} from aqueous solution by ion exchange on vermiculite. By D. C. Sammon and R. E. Watts. H.M.S.O., 4s.

An examination of ion-exchange methods of treatment of radioactive waste with particular reference to Cs^{137} and Sr^{90}. The investigation is, however, directed to the properties of vermiculite as a bed material and comparisons are carried out between its behaviour in crude and exfoliated form.

AERE M619. The occurrence of chlorine in electrodeposited beryllium. By R. G. Bellamy, H.M.S.O., 3s.

This report surveys the existing data on chlorine in beryllium. It has been discovered that in electrolytic beryllium 200-300 ppm of chlorine remain and it is concluded that these must be inclusions of a chloride electrolyte, and investigations show that they cannot be simple chlorides. Since even this content of chlorine may significantly reduce corrosion resistance some effort was directed towards the removal but, although the investigations are as yet incomplete, it is stated that the reduction of chloride inclusions below the amount stated can only be carried out by vacuum melting.

AERE M667. Experimental techniques in the study of the reaction between carbon dioxide and graphite under radiation. By N. S. Corney, W. R. Marsh and J. Wright. H.M.S.O., 2s. 6d.

The behaviour of carbon dioxide and graphite under radiation conditions is a very important subject to the reactor designer who, however, is interested in a period as long as twenty years, and it is not easy to devise experimental methods which can be carried out in a convenient time, and extrapolated with accuracy. This report reviews certain of the experimental methods in use: gas circulating systems, sealed tube experiments, lamp experiments in BEPO, experiments using isotopic carbon, miscellaneous experimental methods, and gas analytical methods, and attempts an appraisal of their relative merits.

AERE R3216. Methods of calculation for use in the design of shields for power reactors. By A. F. Avery, D. E. Bendall, J. Butler, K. T. Spinney (Harwell). H.M.S.O., 25s.

Radiation shielding design, as this report points out, is not yet an exact science, and far too much reliance is placed upon empirical methods, professional know-how, or plain guesswork. Reliable methods of calculation could result in substantial savings—as large as £100,000 per reactor in some cases.

The report sets out to provide recommended methods for shield design which would satisfy four requirements: accuracy, ease of application, minimum use of empirical formulæ, standardization of

method. This last is considered of particular importance since, if it can be achieved without loss of accuracy, it makes it much easier to compare different designs. A new method of calculating neutron penetration is discussed, and compared with experimental results. Other topics dealt with include heating of shields, coolant activation and radiation streaming.

The use of a high-speed computer is necessary for some of the work and an account is given of the RASH B programme for the Ferranti Mercury computer; appendices give further details of this programme, and of a similar programme for gamma radiation, known as GASH B.

AERE R3391. Design and engineering problems of the spent fuel element irradiation ponds at AERE, Harwell. By J. W. Mark. (H.M.S.O., 7s.)

Spent fuel elements from DIDO and PLUTO were at one time deposited in storage blocks for 100 days after removal from the reactor, dry-sheared and the fuel plates sent to Dounreay for reprocessing. The purpose of these ponds is to use the spent fuel elements during the delay period as high-energy irradiation sources; it is expected that a maximum activity of 2 Mc will be available. Fuel elements now remain in the reactor for 12 hours after shut-down, after which they are placed in the internal storage block for not less than one day. They are then transferred to the irradiation ponds in a mobile flask, sheared under water, and the fuel plates, if undamaged, retained for use as irradiation sources. Their useful life is usually about 100 days, during which the activity declines from approximately 60 kc to 2 kc per element, after which they are discarded and sent for reprocessing.

This paper describes in some detail the design and construction of the ponds and their associated shearing and handling plant, including the temporary canning used for both the irradiated elements and the samples for irradiation. It is well illustrated by drawings and photographs.

MEETINGS

October 25. The Institute of Marine Engineers (Joint Panel on Nuclear Marine Propulsion, in conjunction with the B.N.E.C.). **Some observations on the design and construction of the N.S. *Savannah*.** J. A. Dodd and S. Macdonald.

November 2.—The Institution of Electrical Engineers. (Southern Centre, at the University, Southampton, 7.00 p.m.) **The electrical simulation of heat flow in the analysis of cooling systems for electrical equipment.** B. M. Weedy, B.Sc.(Eng.).

November 8.—The Institution of Electrical Engineers. (Northern Ireland Centre, at the Civil Engineering Department, David Keir Building, The Queen's University, Stranmillis Road, Belfast. 6.30 p.m.) **The application of irradiation in industry.** M. C. Crowley-Milling, M.A.

November 8.—The Institution of Civil Engineers (in conjunction with the B.N.E.C., 5.30 p.m.). **Some contributions from nuclear power to engineering practice.** Ian Davidson.

November 9-10.—The Institution of Mechanical Engineers (in conjunction with the B.N.E.C.). Symposium on **The use of secondary surfaces for heat transfer with clean gases.**

November 14.—The Institution of Electrical Engineers. (North-Eastern Measurement and Electronics Group, at the Rutherford College of Technology, Northumberland Road, Newcastle upon Tyne, 6.15 p.m.) **Thermistors—their theory, manufacture and application.** R. W. A. Scarr, B.Sc. (Eng.), Ph.D. and R. A. Setterington, B.Sc.(Eng.).

November 15.—The Institution of Electrical Engineers. (Measurement and Control Section, 5.30 p.m.) **Discrete analogue-computer compensation of sampled-data control systems.** T. Glucharoff, M.E. (read by J. H. Westcott, B.Sc.(Eng.), Ph.D.).

November 17.—The Society of Instrument Technology. (Control Section, London, at Manson House, 26 Portland Place, W.1, 6.30 p.m.) **The control of a single-effect concentrating evaporator—dynamic characteristics and analogue computer study.** F. P. Lees, M.A., B.Sc., L. W. A. Glasson, M.Eng., and J. A. Anderson, S.L.U. Ing.

November 24.—The Society of Instrument Technology. (Data Processing Section, London, at Manson House, 26 Portland Place, W.1. 6.30 p.m.) Symposium on Nuclear Temperature Scanning. **Temperature scanning equipment for a large nuclear reactor.** C. Hall, B.Sc. **Temperature scanning equipment for use in a nuclear power station.** A. G. Blay, M.Sc., A.M.I.E.E., P. G. Davey, M.A., and F. C. Flint.

NEW BOOKS

Glossary of Atomic Terms. (54 pp. P.R. Branch, U.K. Atomic Energy Authority, 11 Charles Street, London, S.W.1. 3s. 6d.)

A short glossary intended for journalists, teachers and laymen in which some five hundred terms in common use are explained in simple language. The present booklet is a revised edition of one first issued in 1958, and will be found useful even by those who feel that they do not normally need a glossary, since many semi-slang terms are included.

Large Radiation Sources in Industry, Volume I, Conference Proceedings, Warsaw, 8-12 September, 1959. (478 pp. International Atomic Energy Agency. 27s.)

A report of the proceedings of the conference on the application of large radiation sources in industry, especially to chemical processes, organized by the International Atomic Energy Agency in Warsaw, September 8-12, 1959. Although the general opinion expressed at the conference was that the industrial exploitation of large radiation sources on a major scale was very far distant this summary is a useful review of the general status of the technology. The book is divided into five sections—Large Radiation Sources and Methods of Use, Cobalt-60 and Other Radiation Facilities, The Use of Fission Fragments Recoil Energy for Chemical Processing, Radiation Effects on Plastics and Elastomers and, finally, Radiation Initiation of Polymerization and Grafting.

It would have been much more useful however, if the book had been produced in a single language. The papers are published in their original tongue with summaries in English, French, Spanish and Russian. If this had been done as a matter of urgency in order to get the proceedings published rapidly then there would have been some justification for the method but, in fact, the volume has taken nearly 12 months to produce which should have allowed ample opportunity for full translations. As a documentary recording, therefore, the book will serve a useful purpose but its value either as reading or reference material to the average reader is bound to be limited.

Books Received

Lloyd's Register of Shipping. (History.) By George Blake. 194 pp. Lloyd's Register of Shipping. 42s.

Progress in Automation. By Andrew D. Booth. 231 pp. Butterworths Publications, Ltd. 42s.

Thermodynamics and the Heat Engine. By Donald H. Marter. 812 pp. Thames and Hudson, Ltd. 63s.

Nuclear Photo-Disintegration. By J. S. Levinger. 144 pp., 21 illus. Oxford University Press. 15s.

Radioisotopes, A New Tool for Industry. By Sidney Jefferson, B.Sc., A.C.G.I. 174 pp., 80 illus. (Second Edition). George Newnes, Ltd. 21s.

Nuclear Fusion. Edited by William P. Allis. 488 pp., 222 illus. D. Van Nostrand Co., Ltd. 94s.

British Nuclear Reactors. By Gerard Gibbons and Kenneth Jay. 32 pp., 40 illus. Chatto and Windus, Ltd. 6s. 6d.

Neutron Detection. By W. D. Allen, B.Sc., D.Phil. 260 pp., 105 illus. George Newnes, Ltd. 45s.

Atom-ABC. (German.) By W. D. Muller. 320 pp. Econ-Verlag G.m.b.H., Dusseldorf. DM 12.80.

Nuclear Ship Propulsion. By Holmes F. Crouch. 334 pp., 133 illus. Cornell Maritime Press (Putnam and Co., Ltd.) 87s. 6d.

Radiation Pyrometry and its Underlying Principles of Heat Transfer. By Thomas R. Harrison. 234 pp., 46 illus. (John Wiley and Sons, Inc.) Chapman and Hall. 96s.

Radioisotope Laboratory Techniques. By R. A. Faires and B. H. Parks. 244 pp., 92 illus. George Newnes, Ltd. (Second Edition.) 25s.

Basic Principles of Nuclear Science and Reactors. By Alan M. Jacobs, Donald E. Kline and Forrest J. Remick. 262 pp., 144 illus. D. Van Nostrand Co., Ltd. 49s.

Reactor Handbook. Vol. I. Materials. Edited by C. R. Tipton Jr. 1,207 pp. Interscience Publishers, Ltd. 260s.

Power from Atoms. By Egon Larsen. 142 pp. Frederick Muller, Ltd. 9s. 6d.

Progress in Metallurgical Technology. (The Institution of Metallurgists). 147 pp. Iliffe and Sons, Ltd. 32s. 6d.

Extractive and Physical Metallurgy of Plutonium and its Alloys. Edited by W. D. Wilkinson. 314 pp. Interscience Publishers Inc. 79s.

Radioactive Wastes, their Treatment and Disposal. Edited by John C. Collins. 239 pp. E. and F. N. Spon, Ltd. 55s.

Federation of Civil Engineering Contractors Handbook 1960-1. 303 pp. 12s. 6d.

Lead Isotopes in Geology. By R. D. Russell and R. M. Farquhar. 243 pp. Interscience Publishers Inc. 65s.

Heat Transfer Engineering. By H. Schenck. 314 pp. Longmans Green and Co. 28s.

Atomic and Nuclear Physics. By Robert S. Shankland (second edition). 665 pp. The Macmillan Company, New York. 49s.

Plasma Physics and the Problem of Controlled Thermonuclear Research. Vol. 2. Edited by M. A. Leontovich. (Translation from the Russian). 457 pp. Pergamon Press. 160s.

The Advance Science Masters Handbook. Compiled by Ivan L. Muter. 124 pp. Advance Components, Ltd. 12s. 6d.

Progress in Nuclear Energy. Vol. 2. Technology, Engineering and Safety. Edited by C. M. Nicholls, R. Hurst and R. N. Lyon. 822 pp. Pergamon Press. 105s.

Kernergie-Technik (in German). By H. Engel and K. O. Thielheim. Verlag Moderne Industrie. 300 pp. DM 36.

Processes and Equipment

For further information on any item please enter the relevant number on the Reader Service Card enclosed with this issue and forward the card to the address given.

Sub-micron Filter

A previous review (*Nuclear Engineering*, June, 1960, p. 285) of the Kent "Jetstream" heavy-duty vacuum cleaner made brief reference to a sub-micron filter which could be fitted for nuclear or hospital work. Through the courtesy of the manufacturers, we have now been able to find out a little more about this filter, and about a new design with even more promising performance.

The filter operates upon the impact principle; i.e., instead of a "sieving" action, it relies on the particle striking, and by electrostatic action sticking to, one of the filter fibres which it must meet in its tortuous path through a pad of exceedingly fine glass fibre which is loosely woven so as not to cause an excessive pressure drop. To use a homely simile, the action could be compared with that of a bramble bush, which offers very little wind resistance, but through which it is not possible to pass without being caught by a branch.

Claims of filtration down to a particle size of 0.3 μ appear to have been substantiated by tests, and in addition to the medical world, the U.K. AEA has ordered a number of machines, including several with special dust containers of ever-safe geometry.

The new filter, not yet in quantity production, has an even more impressive performance. It consists of a specially woven glass fibre paper, and is arranged in a more or less conventional labyrinthine form, to enable a container suitable for fitting into a machine of normal size to carry a filter area of some 25 ft². Tests have been carried out by Surgeon-Cdr. Darlow, of the Porton microbiological laboratories, and preliminary results with methylene blue show that at an air flow of 150 ft³/min the penetration of particles in the range 0.01-1.0 μ was 0.000005%.

(Kent Floor Machine Co., Ltd., Speke, Liverpool, 24.)

1370

Hard P.V.C. Pipes

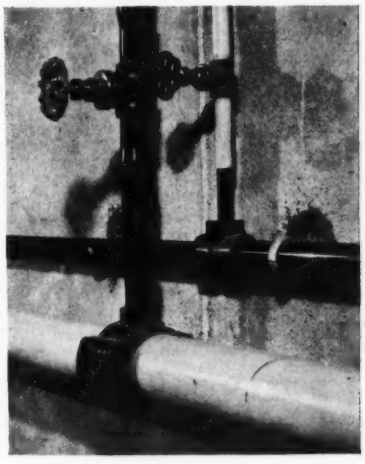
Hard, or unplasticized p.v.c. extruded pipes are often considered to have several advantages over more conventional materials for water supplies and, although not yet in general use in this country, are widely used overseas. In Holland, for example, some 155,000 houses were so connected by the end of 1957. The material would, however, appear to be attractive for industrial purposes since, apart from acetone, ketones, benzene or organic solvents, pipes will give good service with a wide range of acids, caustic solutions and other troublesome liquids, while low cost, light weight and ease of manipulation would appear to render them attractive for water.

Wavin pipes are made in Ireland in a range of grades and sizes. Service and distribution pipes are made in seven nominal sizes from ½ in.-1¼ in. for service up to 130 p.s.i., jointing being carried out with cement. Thick-wall pipes, made in seven sizes from ½ in.-2 in., allow of a B.S.21 thread to be cut, and screwed fittings in p.v.c. are available. Water main pipe is made in sizes from 2 in.-6 in., in three grades, for pressures of 87, 130 and 173 p.s.i. respectively, and are light enough to allow lengths up to 200 yards to be jointed before being dropped into the trench.

(Wavin Pipes, Ltd., Cian Park, Drumcondra, Dublin.)

1371

Wavin main and service pipes with saddle and tee-piece in hard p.v.c.



On-the-spot Labelling

Instant and permanent identification of cables, pipes, controls and, in fact, practically any piece of equipment is possible with the Hellermann "Dymo-mite," a compact hand tool which produces embossed labels

The Hellermann Dymo-mite.

as required, in a matter of minutes, from a roll of metal or plastics tape ½ in. wide, contained in the handle, and crops the label to the length required by a built-in cut-off tool.

The range of tapes available is extensive, and covers monel, stainless steel, copper, and zinc in plain form, and aluminium tape either plain or backed with a pressure-sensitive adhesive. Vinyl tapes, in which the lettering is embossed in white, are available either with or without adhesive backing, in blue, green, red, brown, clear, black, and yellow. All tapes can be supplied edge-printed with a company name, or other unchanging information.

(Hellermann, Ltd., Crawley, Sussex.)

1372

Centrally Patched Analogue Computer

The Panellit G-PAC Mk. II computer has been developed as an extension to the range of analogue computing equipment, and combines the convenience of a centrally patched computer with the flexibility of direct patching between units. The use of modular construction with plug-in brick units not only simplifies maintenance, but allows the installation to be expanded; the design is such that it can be integrated with an existing Mk. I installation.

The G-PAC Mk. II computer.

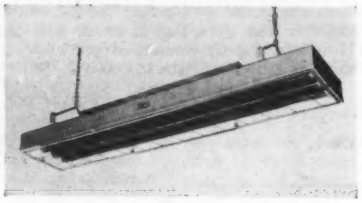
Equipment of the Mk. II includes 20 summing and integrating amplifiers; 40 ten-turn helical potentiometers; three servo-multipliers, each of which can have up to five function potentiometers, and five amplifier positions, which can be used to accommodate any of the standard non-linear units, or special units for a particular problem. The central patch panel has removable problem boards, allowing rapid change of problem, and increasing the computer availability, since new problems can be patched away from the equipment.

(Panellit Ltd., c/o Elliott Brothers (London), Ltd., Elstree Way, Borehamwood, Hertfordshire.)

1373

Ultra-violet Inspection

The increasing use of ultra-violet light for inspection purposes—particularly with fluorescent inks for crack detection, has created a need for large sources of u.v. illumination. Fittings recently marketed use four fluorescent tubes (either 2 ft or 4 ft) in



The Allen ultra-violet fitting.

a steel trough fitting with aluminium reflector, and will provide a high level of u.v. radiation over a wide area.

The use of fluorescent tubes in place of high-pressure mercury lamps avoids the delay of the "warm-up" period, and they can be switched on and off as required. Woods glass is used for the tubes, and the phosphor has a peak radiation in the 3,500-3,700 Å band; there is practically no visible radiation, and none below 3,100 Å, so that safety precautions are not necessary. Total consumption, including the control gear losses, is 100 W for the 2-ft model and 180 W for the 4-ft size.

(P. W. Allen and Co., 253 Liverpool Road, London, N.1.)

1374

The Educt-o-Matic contained blast cleaner in use.

Portable Blast Cleaner

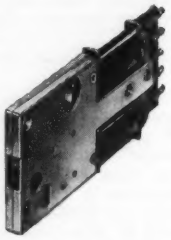
The advantages of vacuum shot-blasting, in which the abrasive action is confined to the area immediately under the nozzle, and the abrasive is continuously removed by vacuum, scarcely need emphasizing for open-shop work. A new unit, the Educt-o-Matic, weighs only 7 lb, and is the size of a hand vacuum cleaner. Operating from a ¾-in. air line (consumption 33-60 ft³/min at 90-100 p.s.i.) it gives a blast pattern 1-1½ in. diameter, the abrasive being continuously recirculated, with very little wastage, so that a 4 lb charge will last from 15-40 min, according to the skill of the operator. The abrasive is passed through a cyclone after pick-up, to remove dust and surface material, which is collected in a separate dust bag. Alternative nozzles are available for edge cleaning, and for the insides of 90° angles.

(Hodge Clemco Ltd., Victor Engineering Works, New Road, Rainham, Essex.)

1375

Electromechanical Counters

Versatility is the keynote of a new range of T.M.C. electromechanical counters, the Elmeg. They are produced in printout or read-out form, operate at up to 40 impulses/sec, at up to 240 V, can have zero resetting by electrical or mechanical means,



The Elmeg EDZ 12A printout counter.

and may be fitted with auxiliary contacts. Surface or flush mounting, they are produced in a wide variety of different forms. Illustrated is a noteworthy example of the range, a single decade printout counter of very slim form, with self-homing reset.

(Telephone Manufacturing Co., Ltd., Hollingsworth Works, Martell Road, London, S.E.21.)

1376

Diaphragm-operated Valves

Uniflow "800" series diaphragm-operated valves, for direct or reverse operation, have been designed for high-pressure work with a variety of semi-corrosive liquids, and are available in sizes from ¼ in.-1 in. The bodies, which are machined from solid bar stock, may be in brass, steel, stainless steel, aluminium or special alloys. Plastics bodies are also available. Standard pressure ratings are 800 p.s.i. for brass, 5,000 p.s.i. for stainless steel; 15,000 p.s.i. for steel. Special bodies for work up to 60,000 p.s.i. can be supplied if required. All valve plugs and seatings are removable and are lapped to ensure tight shut-off. Flow control is governed by the shape of the grooves in the plug, and flow ranges of 50-1 can be obtained.

Uniflow "800" series diaphragm - operated valve.

(British Arca Regulators, Ltd., Sisson Road, Gloucester.)

1377

Specialized Fasteners

A new division of the Unbrako Socket Screw Co., Ltd., known as Unbrako AD, has been formed, which will specialize in

BRIEFLY . . .

Latest addition to the range of dry bearing materials produced by **Bound Brook Bearings, Ltd.,** Trent Valley Trading Estate, Lichfield, Staffs, is Polyslip 1M, a porous bronze material impregnated with p.t.f.e. and lead additive, which gives 4-5 times the performance of the original Polyslip material. Standard sizes are based on B.S.1131 pt. 5, to give internal diameters in 14 logical steps between 3/16 in. and 2½ in., with two lengths to each diameter. **B179**

Henry Wiggins and Co., Ltd., Thames House, Millbank, London, S.W.1, announce a new alloy, Nimonic 115, with a test specification of 7 tons/in.² at 980°C, with a life to rupture of 75 hours minimum, a considerable increase over the previous alloy (Nimonic 105), showing an increase in operating temperature plus a 50% increase in creep life. **B180**

A new automatic welding process has been introduced by **Rockweld, Ltd.,** Commerce Way, Croydon, Surrey. Known as the Comatic process, it is intended for fast vertical welding of plates down to ½ in. thick by a shielded arc, the molten weld metal being contained by water-cooled copper shoes which traverse upwards with the carriage as welding proceeds. **B181**

A new rust remover known as "Pitan," non-combustible and non-toxic and containing no phosphoric and hydrochloric acid, is announced by **Allweather Paints, Ltd.,** 36 Gt. Queen Street, London, W.C.2. **B182**

Westinghouse Electric International Company, 40 Wall Street, New York, 5, announce the introduction of tunnel diodes made of germanium crystal produced by a controlled dendritic growing process. **B183**

Stewart Wales, Somerville, Ltd., Calderbank House, 99 Brownside Road, Cambuslang, Glasgow, announce Galvalloy, a new anti-corrosive medium, which, it is stated, upon drying separates into two distinct parallel layers of different electro-potentials, the upper protecting the lower. Results are said to be equal to hot dip galvanizing, the material being self-healing for minor abrasions, and withstanding red heat. **B184**

Siebe, Gorman and Co., Ltd., Neptune Works, Davis Road, Chessington, Surrey, announce that their Mark 4 compressed air breathing apparatus as supplied to the AEA, has been approved by the Chief Inspector of Factories under the Chemical Works Regulations, 1922. **B185**

A lithium-based all-purpose grease offering extreme pressure lubrication over a temperature range from 32° to 300°F, is now being distributed in the U.K. by **Bardahl Products, Ltd.,** 39 Craven Road, London, W.2. **B186**

Detel Products, Ltd., Stonefield Way, Victoria Road, South Ruislip, Middx, have sent us a performance bulletin of their epoxy-pitch paint applied to bare metal without primer, under salt spray and weathering tests. **B187**

New and improved models of the Waters torque gauge, in sizes up to ¼ in. capacity, are announced by **International Engineering Concessionaires, Ltd.,** 39 Parliament Street, London, S.W.1. **B188**

A new welding electrode, known as "Opal 3½ Ni," has been developed by **Cooper and Turner, Ltd.,** Vulcan Works, Vulcan Road, Sheffield, 9, for the welding of low carbon 3½% nickel and similar steels where good Charpy impact values are required at sub-zero temperatures. **B189**

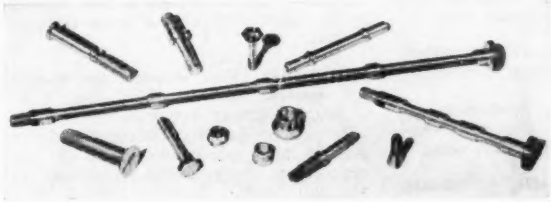
high-performance fasteners, particularly for high-temperature operation. A very wide range of standard and special fastener units, in a number of materials including titanium, Nimonic, and other alloys is available.

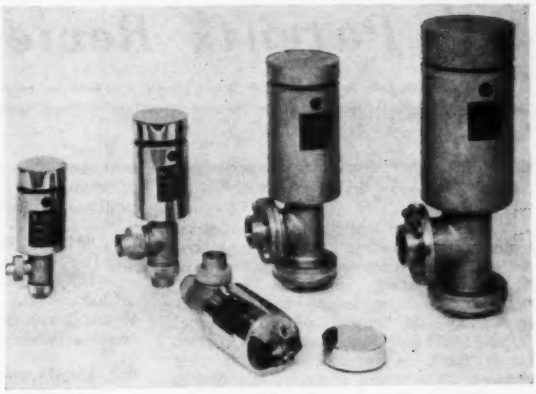
(Unbrako Socket Screw Co. Ltd., Burnaby Road, Coventry.)

1378

(Right) A group of N.G.N. magnetically operated vacuum valves.

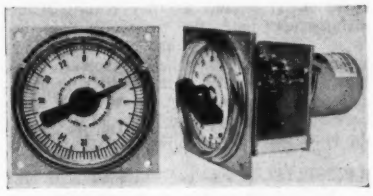
(Below) Typical Unbrako high-performance fasteners.





Synchronous Timer

A new Elremco hand-set synchronous timer, the NHR, has been designed to take the place of the earlier HR type, retaining the same mounting (3⅛ in. hole) but with a new internal mechanism. Either one or two



The new Elremco synchronous timer.

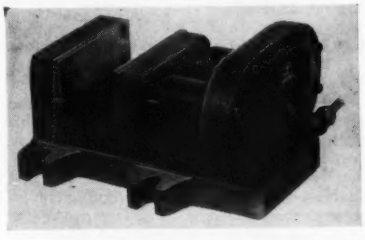
changeover micro-switches (capacity 6 A, at 230 V) are fitted as standard, but up to 12 timed circuits can be fitted if required. The most popular time ranges are 0-60 sec, 0-5, 0-15, 0-60 min, and 0-6 hours, but ranges from 0-30 sec to 0-7 days can be supplied.

(Electrical Remote Control Co., Ltd., Bush Fair, Tye Green, Harlow New Town, Essex.)

1379

Pneumatic Vice

Developed in Holland, and now available in this country, the Morrisflex-Grasso pneumatic vice, model M.12, is a very convenient method for quickly securing work in a firm



The Morrisflex-Grasso pneumatic vice.

grip. Primarily intended for rapid handling of repetition work, it has the advantage of avoiding damage to the operator's hands since, although the maximum gap, which is rapidly adjustable, is over 5 in., the actual movement under power is only 0.1 in.

(B. O. Morris, Ltd., Morrisflex Works, Briton Road, Coventry, Warwickshire.)

1380

Magnetic Valves for High Vacua

A range of magnetically operated valves for high-vacuum work has been introduced in a range of eight standard sizes, from ¼ in.-4 in., all suitable for operation in about ½-1 sec, against a pressure difference of 15 p.s.i.; faster operation can be provided if specially required. Sealing is between a Nygon vacuum-rubber pad and a brass or stainless steel cone; special body plating and stainless steel adaptors can be provided for mercury-contaminated systems. Operation is from 160-180 V d.c., or from 200-250 V a.c., with a built-in rectifier. Auxiliary contacts can be provided for interlocking.

(N.G.N. Electrical, Ltd., Avenue Parade, Accrington, Lancs.)

1381

"Vista" Instruments

Open scales and shadowless readings are the main features of the new Taylor "Vista" range of panel-mounting instruments, produced in various colours to harmonize with existing equipment, and designed so that they can be interchanged

A Taylor "Vista" micro-ammeter.

with earlier designs. Four models are available, with nominal scale lengths from 1⅛ in.-4½ in. The movement is the well-known centre pole type, and d.c. sensitivities as low as 5 μA full-scale can be obtained. Ranges available include m.c. with thermocouple or rectifier, and m.i. ammeters and voltmeters. Mirror scales and knife-edge or spade pointers can be supplied to special requirements.

(Taylor Electrical Instruments, Ltd., Montrose Avenue, Slough, Bucks.)

1382

Companion to Binal

Following the description given of the boron-aluminium material produced by the "Sinterwrought" process (*Nuclear Engineering*, September, 1960, p. 423), a companion material has now been announced. Bo-Stan, a boron-stainless steel dispersion, is also being produced by the same methods, of sintering and hot-working. Up to 2% boron can be incorporated at present; larger contents are expected to be available before long.

(Sintercast Division, Chromalloy Corporation, 132 Woodworth Avenue, Yonkers 2, New York.)

1383

CATALOGUES

A new general price list of photographic material is to hand from **Ilford Ltd.**, Ilford, Essex.

The main design features of Newman-Velan bonnetless valves for high pressure and high temperature service are described in a publication number 315/8/60, recently issued by **Newman, Hender and Co., Ltd.**, Woodchester, Stroud, Gloucester, which also describes flow control valves with V-ported discs.

Morgan Refractories Ltd., Neston, Wirral, Cheshire, have issued a leaflet, RD.95, which describes "Purox," a range of high quality oxide refractories.

Solid state differential d.c. amplifiers are described in a bulletin received from **Philbrick Researches, Inc.**, 285 Columbus Avenue, Boston 16, Massachusetts, U.S.A.

Saga Supermarine gloss enamel is described in a leaflet issued by **E. Wood Ltd.**, Talbot Works, Stanstead Abbotts, Ware, Herts.

Micro-Systems, Inc., 2925 East Foothill Boulevard, Pasadena, California, U.S.A., have issued a leaflet on bondable semi-conductor strain gauges which are now available in production quantities.

Incoloy DS, heat-resisting nickel-chromium-iron alloy, is described in a publication from **Henry Wiggin and Co. Ltd.**, Wiggin Street, Birmingham 16. This material was formerly known as Nimonic DS.

The "3600 series" armoured flow indicator in sizes from ½ to 1½ in. in ranges from 1.5 gal/h to 50 gal/min for pressures up to 1,500 p.s.i., is described in a leaflet from the **Brooks Instrument Co., Inc.**, Hatfield, Pennsylvania, U.S.A.

"Speedivac" vacuum gauges of the ionisation Pirani and Penning type are described in leaflets published by **Edwards High Vacuum, Ltd.**, Manor Royal, Crawley, Sussex.

Rotork valve actuators are described in a new publication EA2/60 received from the **Rotork Engineering Co., Ltd.**, Bath.

Precious metal thermocouples are described in a new list received from **Engelhard Industries, Ltd.** (Baker Platinum Division), 52 High Holborn, London, W.C.1.

Chemically inert filter media Teflon and Kel-F, with mean pore openings of 9 and 15 μ respectively are described in a leaflet P-103A received from the **Porous Plastic Filter Co., Inc.**, Glen Cove, New York, U.S.A.

An up to date list of "Gredag" greases and compounds including a calcium, sodium and lithium soap base, bentone base and molybdenum disulphide, has been published by **Acheson Colloids, Ltd.**, P.O. Box No. 12, Prince Rock, Plymouth, Devon.

From **Q.V.F., Ltd.**, Duke Street, Fenton, Stoke-on-Trent, Staffs. comes a list of glass distillation units up to 100 litres in size.

Patents Reviewed

These abstracts have been made from British Patent Specifications, complete copies of which can be obtained from the Patent Office, 25 Southampton Street, London, W.C.2, at 3s. 6d. each (including postage).

B.P. 833,647. Nuclear reactors. P. Fortescue. To: U.K. Atomic Energy Authority.

A core element suitable for operation at temperatures exceeding 1,000°C is produced as a tubular container of impermeable neutron-moderating material (graphite, beryllia) containing, loosely and uniformly throughout its length, diluted material (1 part fissile fuel diluted with 5 to 50 parts fertile fuel). A number of such core elements are arranged in spaced relationship in a pressure vessel, each outlet of the elements being connected to a conduit with venting means at their outer ends. Coolant is circulated through the vessel and around the elements.

B.P. 834,365. Control rod assemblies for nuclear reactors. To: Westinghouse Electric Corp. (U.S.A.).

Refers to the coupling mechanism between the control rods and their driving shafts. The rods, e.g., of cruciform cross section have notches or shoulders at their upper ends. The coupling screwed on to the lower end of the driving shaft is provided with four radial slots and with latching levers having cams to engage the shoulders of the control rods when a latch is inserted through the tubular coupling body. The latch pin is secured to an operating rod terminating outside the reactor vessel.

B.P. 834,371. High flux homogeneous nuclear process and reactor with circulating fissile material. To: Esso Research and Eng. Co. (U.S.A.).

High flux nuclear reactors have presented difficulties because of the high heat flux associated with high reaction rates. It has been proposed to use moving fissile material for cooling purposes and to cool the material external to the nuclear reaction zone or core. A homogeneous fluid composition of fissile material is passed through a reaction zone, where a nuclear reaction is maintained, then through a zone (of at least equal cross section) where the same critical conditions would exist, but where a neutron absorbing material is disposed having a capture cross section above 10 barns/atom for neutrons having an energy of 0.025 to 2.5 eV so that this second zone is maintained in a subcritical condition. It is thus possible to operate the reactor at a very high flux (above 10^{15} n/cm², sec) and at heat generation rate above 20 MW per pound of fissile material in the core.

B.P. 834,617. Epithermal thorium power-breeder reactor. To: North American Aviation Inc. (U.S.A.).

The various breeder reactor systems pose problems as to structural materials, heat transfer and control. A highly desirable reactor type would be one which permits use of structural material without regard to cross section (as in a fast reactor), has a core size which will allow efficient heat removal, and a neutron energy spectrum which will permit efficient control. This is achieved in an epithermal, thorium breeder reactor with a core in which uranium fuel is disposed in a moderator (graphite, beryllium, hydrogen, deuterium) within a breeder blanket (thorium) using a liquid metal coolant (sodium) for removing the fission heat.

B.P. 834,663. Remote control manipulator. To: U.S. Atomic Energy Commission (U.S.A.).

Characterized by the substitution of electrical connections for mechanical connections between master and slave units.

B.P. 834,829. Nuclear reactor. R. Schulten (Germany).

A gas-cooled heterogeneous nuclear reactor using as fuel uniformly shaped moulded bodies (spherical, cylindrical, hollow, coarse or fine powder). The reactor is provided with a breeder blanket and a reflector casing which also consists of uniformly shaped bodies of essentially the same form as the fuel elements. A vibrating grid or a screw conveyor removes the used-up fuel elements.

B.P. 834,908. Protective equipment for nuclear reactors. A. E. T. Nye. To: British Thomson-Houston Co., Ltd.

Refers to a bridge circuit for controlling emergency shut-down of a gas-cooled reactor. Under normal conditions an out-of-balance circuit flows through the actuating coils of relays to hold in those relays. When the out-of-balance current has been reduced by a variation of resistance through failure of the mass flow in a circulator of the gas coolant the relays are released and the reactor is shut down.

B.P. 834,965. Measuring device for radioactive fluids. B. A. Bergstedd (Sweden).

In fluid cooled reactors active rare gases may penetrate the fuel elements in amounts indicating a major leak in the protective covering. Sensitive detectors (for alpha, beta and gamma rays) have, therefore, been introduced into the containers or pipes containing the radioactive fluid but this system is not satisfactory as it is non-selective. It has also been proposed to evaporate a test quantity of the fluid in a so-called "plate" to measure the activity of the dry substance. Normally this testing takes place manually. There are certain practical difficulties and evaporation is not quick enough. Evaporation, however, will be increased if the fluid is brought into intimate contact with a gas at high temperature to produce a "spray." This spray is then evaporated as an aerosol and the components filtered in an electrostatic filter, the radioactive particles being deposited on a (stepwise) movable tape to pass successively three detectors, one for alpha, one for beta, and one for gamma rays.

B.P. 834,978. Nuclear reactor with gas cooling. To: Brown, Boveri and Cie. A.G. (Germany).

In order to make homogeneous reactors more economical and permit continuous renewal of solid material and removal of exhausted material, it has been proposed to give the material the form of small moulded (e.g., spherical, cylindrical, hollow) bodies. The output of such reactors shows considerable fluctuation because of constantly changing distances between the bodies. Furthermore, the drop in cooling gas pressure is so great that the power needed for circulation is excessive. These faults may be overcome by making the bodies so heavy that they remain essentially at rest while the cooling gas flows around them (e.g., spheres of a minimum diameter of 3 cm; cylinders of a minimum height and diameter of 3 cm). The power required for the circulation of the cooling gas is then reduced to less than 30% of the gross electrical output.

B.P. 835,132. Fuel elements for nuclear reactors. W. B. Hall. To: U.K. Atomic Energy Authority.

A nuclear fuel rod surrounded by a graphite tube spaced away from the rod enclosed in a protective (beryllium or niobium) sheath.

B.P. 835,145. Fluid circuits, e.g. of nuclear reactors. S. B. Hosegood, B. E. Puffett, J. H. Swain. To: U.K. Atomic Energy Authority.

Enclosing all components within a steel vessel makes their maintenance extremely difficult. This is particularly awkward in the case of electromagnetic pumps for a liquid metal circuit, as they require more maintenance than the remainder of the circuit. This difficulty may be overcome by a special container for the component, fitted into a recess in the vessel wall, with inlet and outlet pipes having suitable seals between container and recess, and a seal at the outer end of the container.

B.P. 835,257. Nuclear reactors. A. R. Kirkpatrick. To: A. C. Parsons and Co., Ltd.

A control rod composed of a series of tubular inserts of a sintered compact of boron and stainless steel powder in a stainless steel sheath.

B.P. 835,266. Nuclear reactor. To: General Electric Co. (U.S.A.).

Reactor and heat exchanger are housed in the same pressure vessel together with a coolant system in the pressure vessel circulating thermally through reactor and heat exchanger.

B.P. 835,448. Winding and haulage equipment. D. S. Morfey. To: British Thomson-Houston Co., Ltd.

A positive mechanical stop (cams and pivoted detent) as a precaution against failure of the electrical control system for stopping the winding motor of a control rod mechanism.

B.P. 835,764. Heterogeneous nuclear reactors. K. H. Dent. To: U.K. Atomic Energy Authority.

Refers to arrangements for charging and discharging fuel elements. A movable chute between apertures in the pressure vessel and locating holes in the core structure with vertical fuel element channels enables access to a group of channels through each aperture. The free end of the chute is moved by a gas operated piston and cylinder arrangement. One aperture gives access to 16 channels.

B.P. 835,947. Cooling of nuclear reactors. R. P. Kinsey. To: U.K. Atomic Energy Authority.

A reactor core vessel is surrounded by a biological shield in a containment vessel. The biological shield is provided with ducts to allow natural convection flow of a heat transfer fluid in a circuit over the core vessel and over the walls of the containment vessel.